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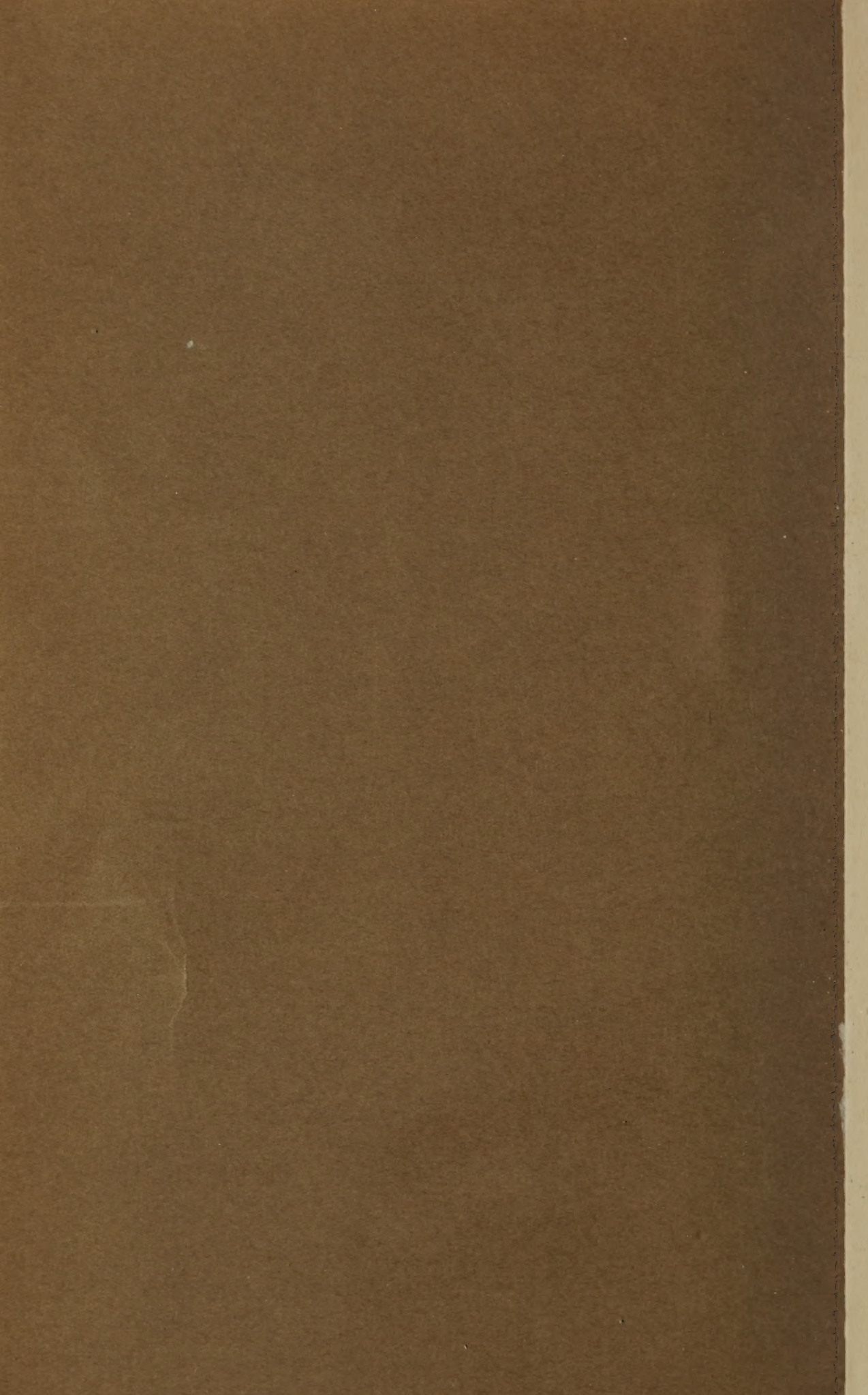


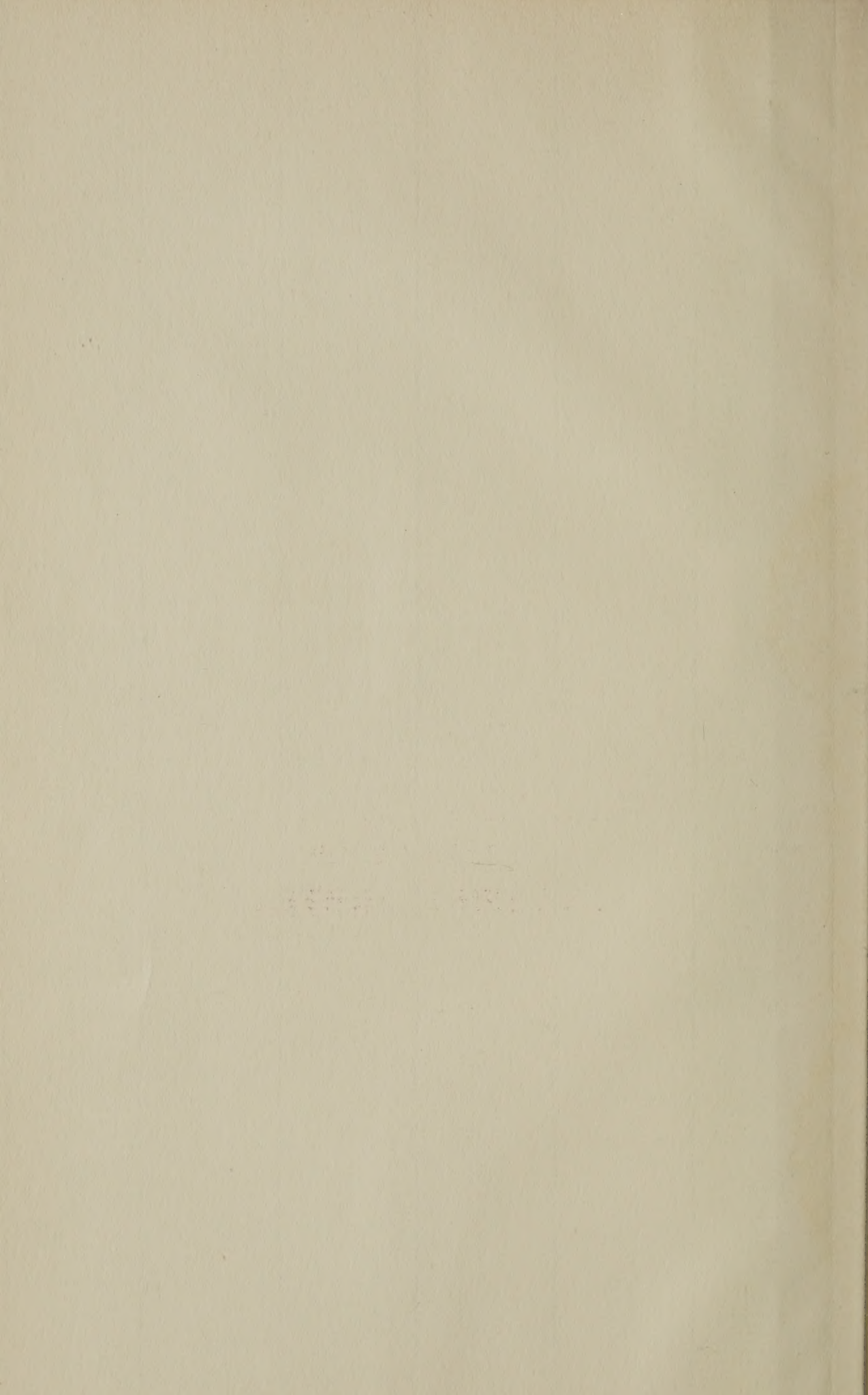
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PRINCIPLES
OF MODERN RADIO
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PRINCIPLES OF MODERN RADIO RECEIVING

By

L. GRANT HECTOR, Ph. D.

Assistant Professor of Physics

University of Buffalo

160 ILLUSTRATIONS

BUFFALO, N. Y.

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PREFACE

THIS book is written for two purposes: the one to give to the intelligent but non-technically trained man a unified picture of the science of radio, its developments and problems; the other, to give some concrete information to the designers, builders, or sellers of sets, and to point the way to further intelligent study. To speak to both these classes in one book is, indeed, a problem. The technical man will doubtless desire greater detail than he will find in some sections, and he will have to use the references given to obtain his information.

The non-technical man, on the other hand, will doubtless miss many of the detailed points given without, it is hoped, even knowing that he has missed them.

This two-fold nature of the book was dictated by its origin. For the past two years the Evening Session of the University of Buffalo has sponsored a course of ten semi-popular lectures on the rather general subject of "Radio." No restrictions were placed on admittance to the course, and consequently the background of students in attendance varied from that of the complete novice to that of graduates of schools of electrical engineering. It was, therefore, necessary to present the material in such a manner as to give the students a fairly coherent picture of the general phenomena of radio communication, and at the same time to supply concrete information for the more technically trained individuals.

The present book is an attempt to present to the public the material of these lectures. It is hoped that it may be sufficiently readable to convey information to the non-technical readers and that it may give the more serious students a stimulus for further and more rigorous study.

The author is indebted to Mr. H. A. Gates for suggestions in the preparation of the material and for reading the proof of the original manuscript.

L. G. HECTOR

Buffalo, N. Y., January 3, 1927



AN INTRODUCTION TO
THE SUBJECT

TOPICAL INDEX

CHAPTER I

General Introduction

Short Analysis of Sound

Piano Tones

Clang Tones

Voice Tones

History and Nature of Radio Wave
Propagation

Damped Waves

Undamped Waves and Modulation

Propagation of Waves through Space

Reception of Signals

Simple Tuned Receiving Circuits

Detectors

Two Element Tube Detectors

Three Element Tube Detectors

Regenerative Detector

Audio Amplification

Loud Speakers

CHAPTER I

An Introduction to The Subject

WE may summarize the whole subject of the technical side of radio by saying that our problem is the conversion of sound vibrations to varying electric currents and back again to sound vibrations without losses or distortion. When a person talks or sings, or a musical instrument is played, actual vibrations of the air particles take place. That such is the case is evident if we consider a simple instrument such as a tuning fork.

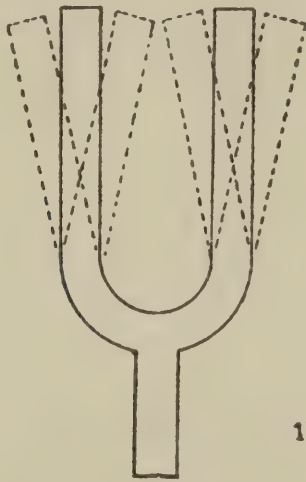


Fig. 1. Vibrating Tuning Fork

When the prongs of the tuning fork spring out as indicated by the dotted lines, the air near the outside of the fork is suddenly compressed. As this compressed air tries to expand to normal pressure it shoves against the air further from the fork so that the air in that region becomes compressed and in this manner the compression is transmitted further and further from the fork. Moreover, the compressed air in the immediate vicinity of the tuning fork, in attempting to return to normal pressure, overdoes itself and becomes less than normal. This condition is increased

by the fact that the prong of the fork is now springing back. So a partial vacuum is created in the immediate vicinity of the fork. Air rushes in from all sides to fill this slight vacuum and in so doing leaves the air further from the fork slightly below normal pressure. In this manner a pulse of rarefaction of the air is also transmitted through the air. So we have alternate compressions and rarefactions of the air progressing outward from the tuning fork. The motion is quite rapid; it is propagated about 1100 feet per second for ordinary conditions of temperature and barometric pressure. The VELOCITY of propagation does not depend on the frequency of vibration of the tuning fork, but is constant regardless of the nature of the source of the sound.

It therefore follows that if the FREQUENCY of vibration of the sounding instrument changes, that the distance from one air compression to the next, that is, the WAVE LENGTH, also changes. The faster the vibration the shorter the wave length of the sound vibration in the air. These common sense considerations lead us to the mathematical expression

$$\lambda F = v$$

where λ is the wave length, F the frequency and v the velocity. Later we shall see that a similar line of thought will lead to a

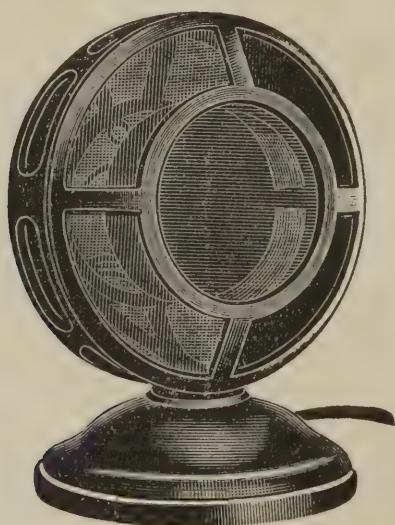


Fig. 2. A Broadcasting Microphone

similar equation connecting the frequency, wave-length and velocity of radio waves.

When the compressions and rarefactions of the air that constitute a sound wave strike a microphone, they are converted into feeble alternating electric currents, or pulsating direct currents. The transmitter of an ordinary wire telephone is, of course, a type of microphone. Since this series of lessons is not primarily concerned with broadcasting we shall not spend time here on the various improvements in microphones that have been made for radio purposes. Suffice it to say that the ones in use in the better stations produce electric currents which follow the vibrations of the sound waves with remarkable fidelity.

The feeble currents of the microphone are amplified by methods quite similar to those employed in the audio frequency amplifiers of radio sets which we shall study in detail later on.

In the broadcasting station itself energy is fed to the antenna by means of very high frequency alternating currents. It is this latter frequency that determines the "wave-length" of the station. The radio waves travel from the station with a velocity of about 300,000,000 meters per second (186,000 miles). If the alternating current fed to the antenna has a frequency of 1,000,000, it follows that the waves will be 300 meters apart and so we speak of a station using a 300-meter wave. We may write here the same type of expression that we did for sound waves: $\lambda_F = v$ where F

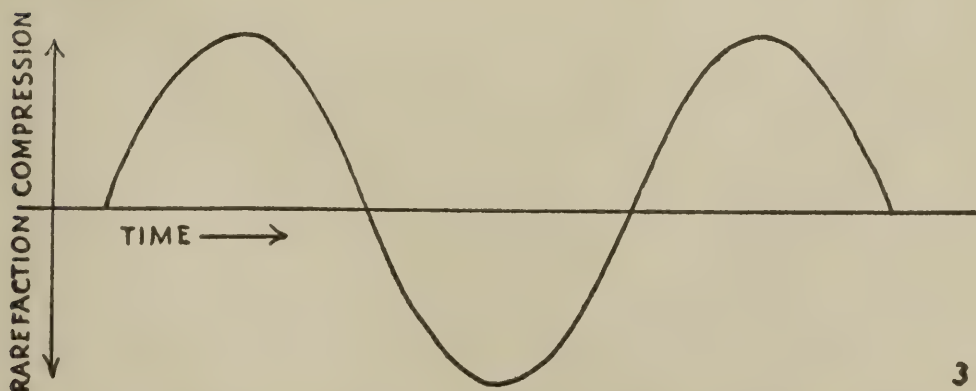


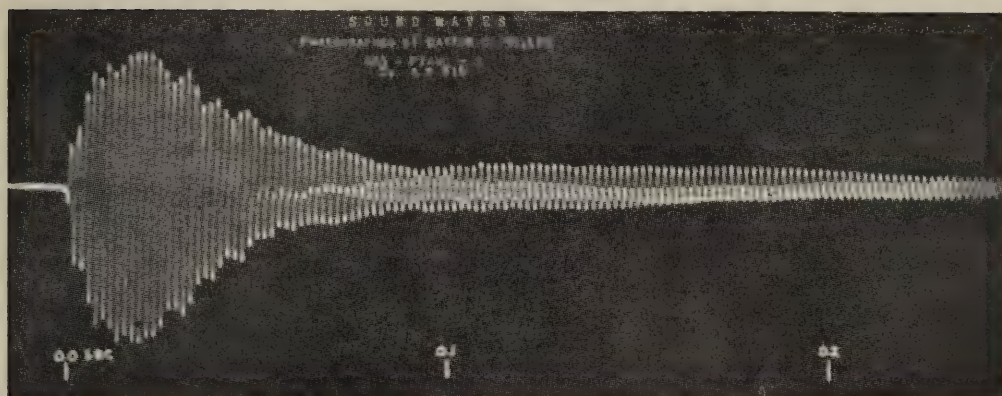
Fig. 3. Graph Showing Variations in the Density of Air when a Simple Sound is Passing Through

is the frequency of alternation of the current, λ the wave-length, and v the velocity with which the radio waves travel.

The alternating currents that come from the microphone are, after amplification, used to control or "modulate" the amount of high frequency current flowing into the antenna.

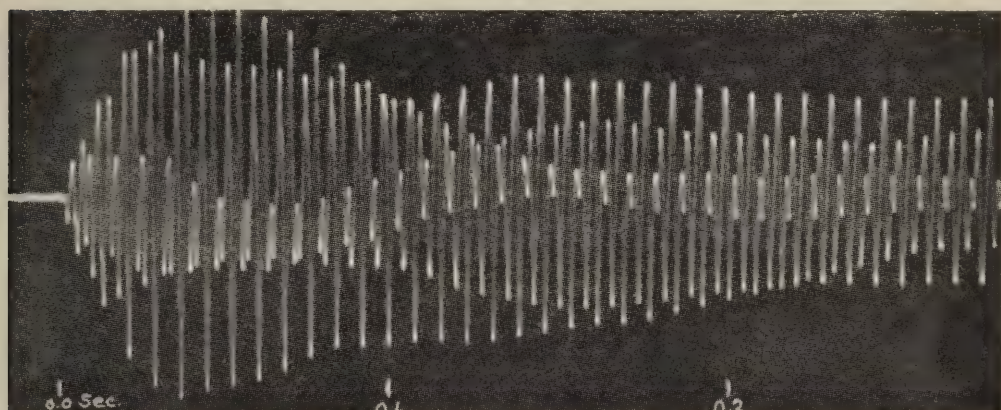
Short Analysis of Sound. We have considered above the simplest form of musical sound that we have. We may represent it graphically by imagining that we could see the wave, its compression and rarefaction regions, in the air. If we let the straight horizontal line represent the region of normal air pressure, points above the line regions where the pressure is above normal, and points below the line regions where there is a rarefaction, and if we let the distance from the line indicate the degree of compression and rarefaction we get a graph such as is shown in Figure 3 for the wave in air of the tuning fork.

Piano Tones. Suppose now that we consider the sound waves produced by a piano. If we touch a key at the low frequency end of the piano we cause a felt hammer to strike a heavy metal string near one of its ends. The result of this method of setting the string into motion is to cause the string to vibrate as a whole and at the same time to vibrate as though it were fastened in the middle so that it acts like a string only half as long as it really is. At the same time there is a tendency to vibrate as though the string were divided into three equal sections, and also four and five, and, for the very low notes, many more. We see then that the "overtones" produced along with the fundamental have frequencies two or three or four, or some other integral number of times the frequency of the fundamental. Professor D. C. Miller of the Case School of Applied Science tells us that on the lowest piano notes frequencies forty times the fundamental may occur. As we go up the piano scale we find fewer harmonics, and in the upper notes the frequencies above twice the value of the fundamental are hardly noticeable at all. Aside from the differences in loudness when the keys are struck with different degrees of hardness we get different relative intensities of the overtones so that the skillful player is able to



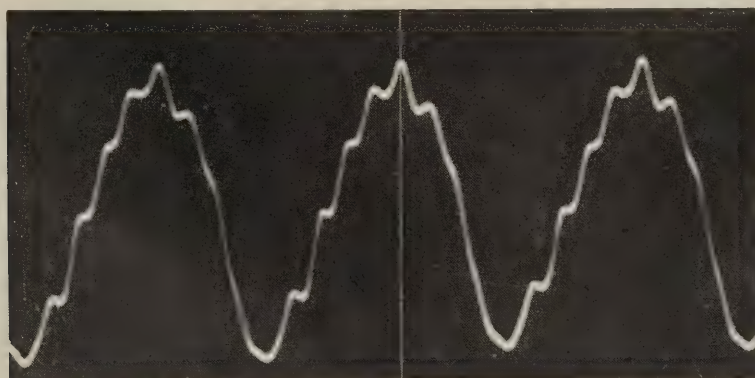
The Science of Musical Sounds—Dayton C. Miller. The MacMillan Co., 1916.

Fig. 4. Piano Tone from the Middle Range. Notice that the overtones seem to increase in intensity while the fundamental dies down after a short interval



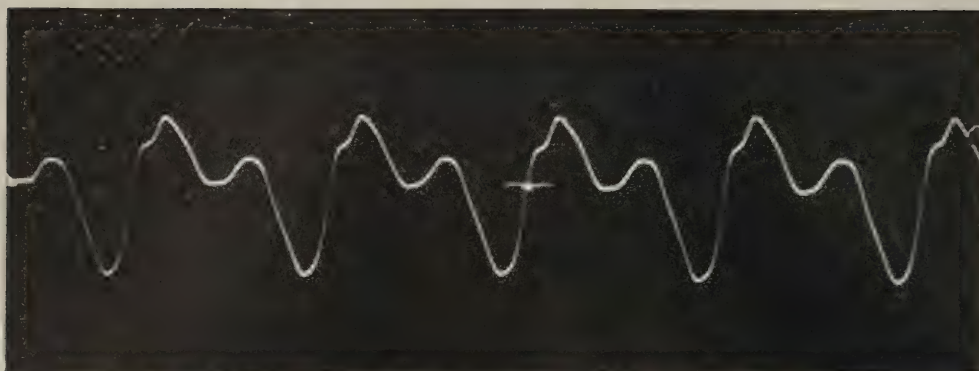
The Science of Musical Sounds—Dayton C. Miller. The MacMillan Co., 1916.

Fig. 5. Piano Tone from a Low Note. Notice that there is a shifting of predominance of one harmonic to another as the tone continues



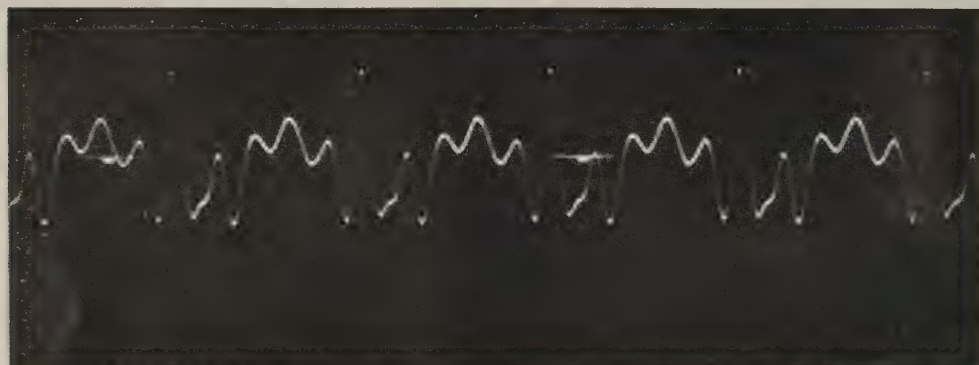
Photograph by Dayton C. Miller

Fig. 6. Violin Tone. The waves in this figure and those of the figures that immediately follow have been spread out more than those of Figure 4 and Figure 5 to show the effects of the harmonics on the general shape of the sound waves



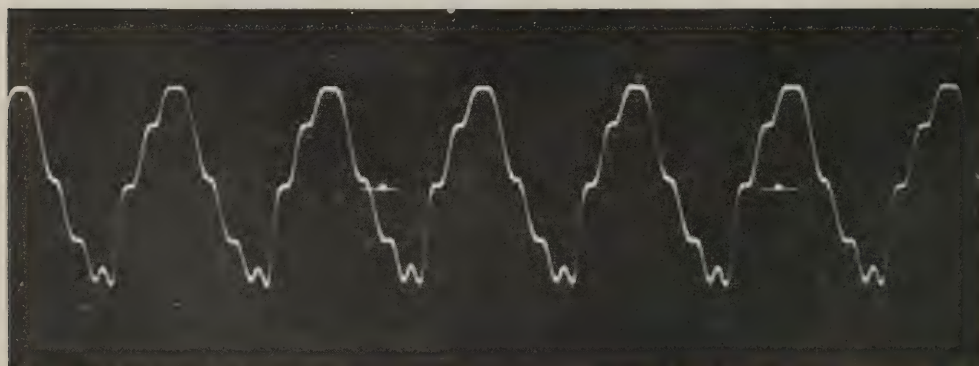
Photograph by Dayton C. Miller

Fig. 7. Flute Tone



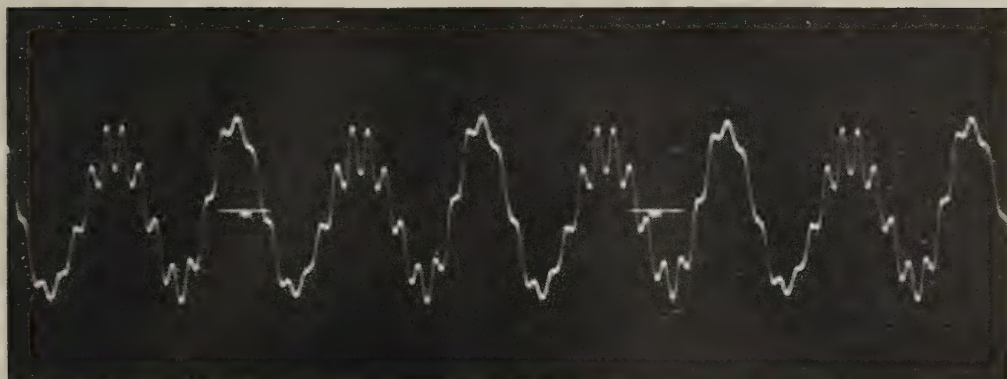
Photograph by Dayton C. Miller

Fig. 6-a. Oboe Tone



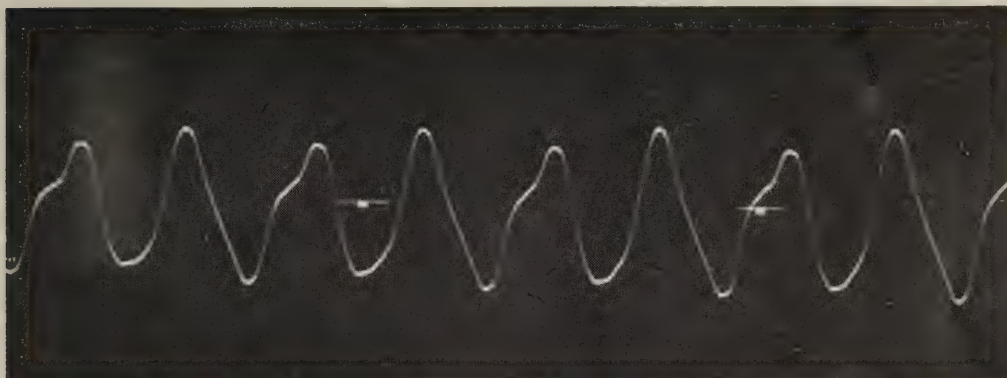
Photograph by Dayton C. Miller

Fig. 7-a. Clarinet Tone



Photograph by Dayton C. Miller

Fig. 6-b. The Vowel E as pronounced in the word BEE

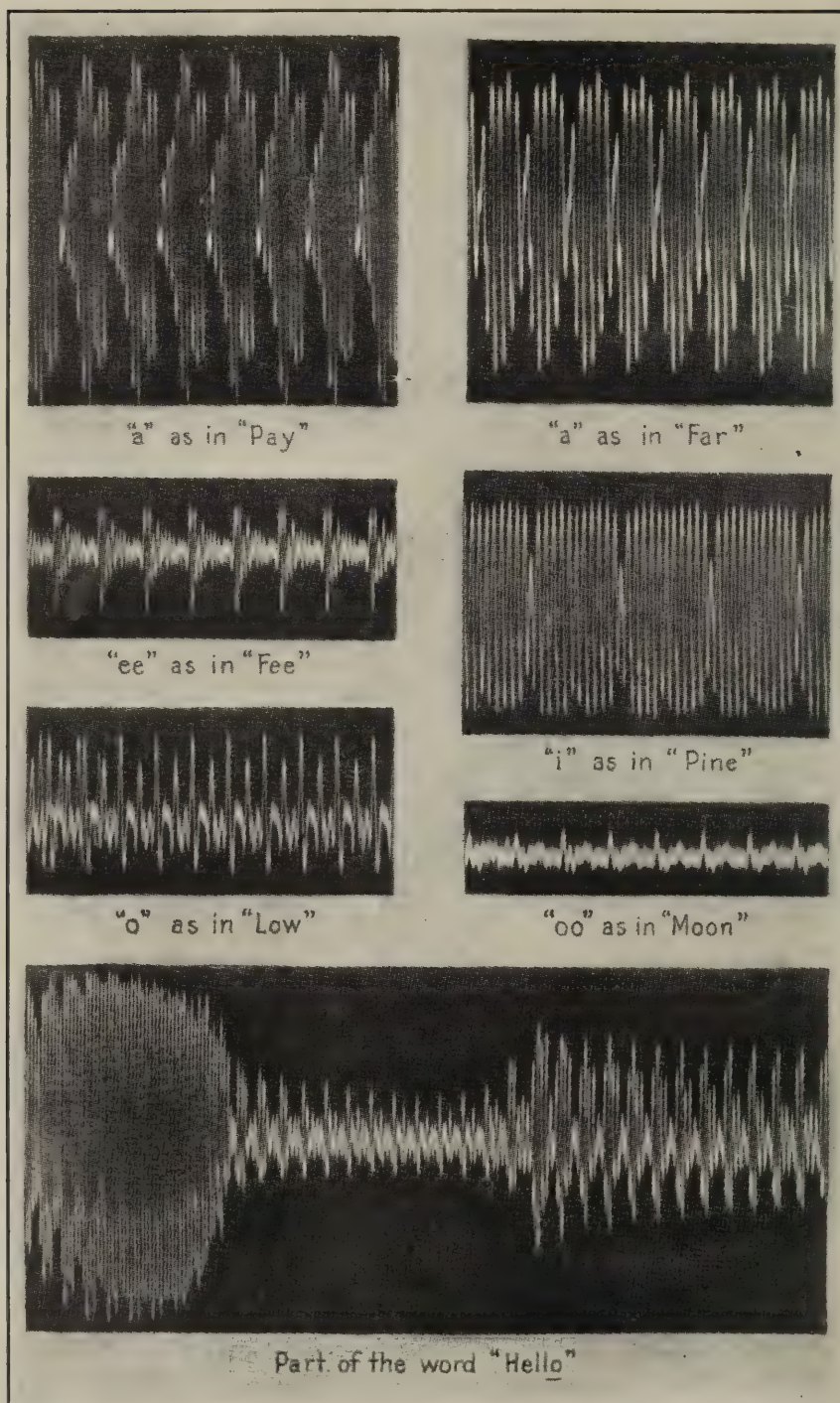


Photograph by Dayton C. Miller

Fig. 7-b. The Vowel OO as pronounced in the word GLOOM

IF a pure tone such as that from a tuning fork were to strike the diaphragm of a microphone, the diaphragm would vibrate to and fro smoothly. If the tone contained strong harmonics as are present in the tones illustrated on these pages, the smooth in and out motions of the diaphragm would be somewhat altered.

It is possible to arrange a mirror and auxiliary apparatus in such fashion as to move a beam of light back and forth in unison with the vibrating diaphragm. When the beam of light is directed at a moving film a photographic record corresponding to the motions of the diaphragm results. When the film is moved rapidly individual motions of the diaphragm are clearly shown while a slow motion of the film shows better the general state of disturbance of the diaphragm for the different tones. This is the general method employed for obtaining the sound wave photographs shown here.



Courtesy of D. Van Nostrand & Co.

Fig. 8. Photographs of Voice Tones

get different tone effects from the same keys and we say he is "interpreting" the music he is playing. As soon as we start to analyze the details of the tones which we expect to be perfectly transmitted and reproduced, we see that our demands are great; and so far we have considered only the tones of the piano.

If we consider the sounds produced by other instruments in addition to the piano we come to the conclusion that the differences in quality of the different instruments depend on the differences in the particular harmonics that are emphasized on each instrument. Note the figures of violin and flute tones.

Clang Tones. If we strike a tuning fork hard with a metallic hammer we get a clanging effect that is not very pleasing. An analysis of this tone shows that a harmonic which is not a simple integral multiple of the fundamental frequency is present. The human ear is pleased only with combinations of sounds where the numerical relations between the pitches of the various tones can be expressed by simple numbers.

Voice Tones. It is also of interest to consider the nature of the sounds of the human voice in the production of words. In both speaking and singing, and especially the latter, we are concerned more with the vowels of words than with the consonant sounds. Perhaps the most simple vowel sound in the English language is the sound given to the *a* in *ma* as pronounced by a child. Suppose that a person makes this vowel sound and also those of other vowels but pronounces them all on the same pitch. (This is called monotoning and is regularly done in some of the more formal churches during the reading of psalms and other parts of the service). We may well ask what it is about the sounds that enables us to tell one vowel from another when all are pronounced on the same fundamental pitch. Or we might ask how we can distinguish the voices of two different people when they speak the same vowel on the same pitch. The answers to both these questions have come to us through a very extensive analysis of sound by Professor D. C. Miller of the Case School of Applied Science in Cleveland. We learn from his research that in addition to the fundamental

frequency at which a person speaks (that is, the frequency that fixes the tone or pitch of the voice) there are multiples (harmonics) of this frequency present. Whether we think the person has said *a* as in *ma* or *o* as in *hoe* depends on the frequency region in which the particular harmonics present occur. We distinguish the voices of individuals by additional harmonics that have little to do with the intelligibility of the vowel sound. The following table represents a fair estimate of the regions in which various voices are likely to pitch the fundamental tones of their spoken words. Their possible singing range is much greater, of course.

Bass	75 to 200	Alto	200 to 400
Baritone	100 to 250	Soprano	250 to 500
Tenor	150 to 300	Small child	350 to 600

But for the tone *a* as in *ma* we would find harmonics in the frequency region around 1050 for every one of the above voices regardless of the particular fundamental used. For *o* as in *hoe* we would find harmonics in the frequency region around 460. For *a* as in *fate* we would find two frequency regions, one around 490 and another at about 2460. Similarly there are distinctive frequencies for all the other vowels.

Essentially the consonants are merely the result of stopping and starting the vowels in different ways. The simplest way gives rise to the common sounds of *m* and *p*, and without doubt it is the simplicity of the sounds of *pa* and *ma* that makes them among the first words that a child learns to say. Occasionally young children seem unable to say certain vowels, and later, as the voices grow lower in fundamental pitch, the children become able to say the vowel. The explanation lies in the fact that if the lowest pitched tone a child can make is above one of the frequency regions necessary for a vowel, then he can not possibly produce that particular vowel sound. A very young girl baby is likely to have difficulty in making a good *e* as in *meet*, because that particular vowel has a characteristic frequency region just above 300, in addition to a high one.

From the above short description of spoken and sung words

one might conclude that it should be possible to arrange musical instruments to produce sounds that would be similar to spoken vowels, or possibly, words. This has been done for one or two of the more simple words by Professor Miller and the success of the experiment is considerable proof of the correctness of this explanation of how we distinguish one word from another and one voice from another.

I have given this discussion of the nature of sound in order that the reader might obtain some idea of the complexity of spoken words and musical tones. Every little variation in the sound wave, every harmonic from every instrument being played, all must be faithfully converted into corresponding electrical vibrations and used to vary the energy input of the broadcasting station. If we assume that the energy is transmitted through space without loss, (and this is hardly true except for points near the stations) we have still the problem of converting these electrical vibrations back into sound vibrations through the medium of our receiving sets and loud speakers, and if the final sound is to seem like the original sound this conversion process must be faithfully performed.

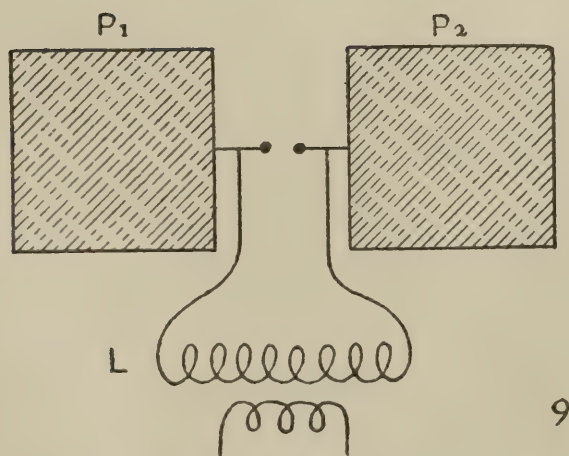


Fig. 9. Hertz Oscillator

History and Nature of Radio Wave Propagation.

In the year 1888, the German physicist Hertz demonstrated that energy of an electro-magnetic nature could be propagated through space and picked up by a suitable receiver.

As early as 1865, Clerk Maxwell, an English physicist, had published a theory concerning the nature of ordinary light and had claimed therein that light was a wave motion in space and was electro-magnetic in nature. Furthermore, his theory showed that it should be possible to project electro-magnetic energy through space in longer wave-lengths than those of ordinary light. Maxwell's theory attracted great attention and was much studied in England with Sir Oliver Lodge at the head of the school of thought. In Italy the study centered about the physicist Righi, and in Germany about Helmholtz and some of his students. It is extremely probable that if Hertz (the protege of Helmholtz) had not made the discovery, it would have been made shortly either by the Italian or the English group of scientists. The oscillators of Hertz were not at all efficient as radiators of energy. In the year 1896 Marconi (pupil of Righi) produced a transmitter which used an outdoor antenna and a ground. This use of a grounded antenna was probably the greatest contribution of Marconi

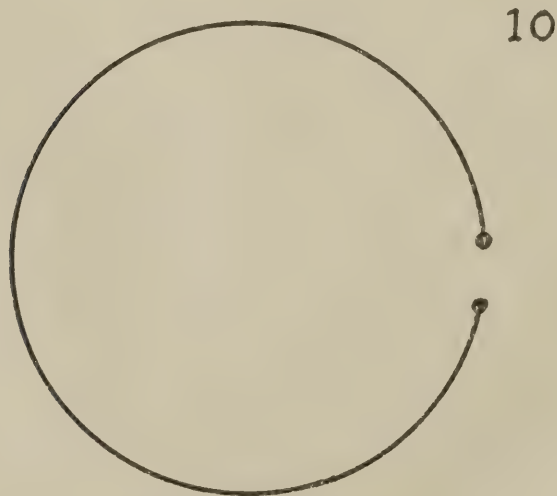


Fig. 10. Hertz Receiver

not excepting any of the work which he has done since. From this time on energy was sent over appreciable distances instead of just across laboratories. In addition to his contribution of the grounded antenna, Marconi's chief aid to the art of radio has been the publicity which he has given it. It was Marconi who

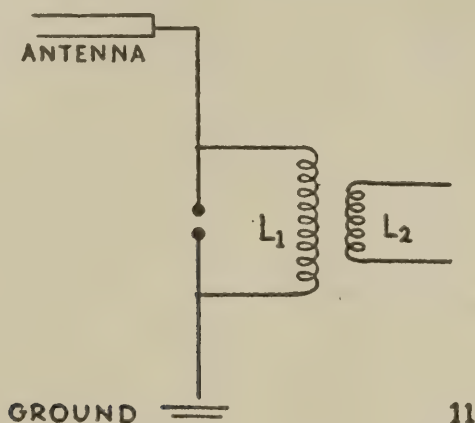


Fig. 11. Marconi Transmitter with Grounded Antenna

first “sold” wireless telegraphy to the public. It was he who shoved it from its position as a scientific toy to a practical position in the affairs of the world.

Suppose that it were possible to connect an antenna and ground to electrical apparatus in such a way as to make the antenna positively charged with electricity with respect to the ground. We would then say that an electric field existed between the antenna and the ground, or we might say that an electrical strain was caused in the space between the ground and antenna. We might now withdraw the source of electric charge and then reconnect it in reverse manner so that the antenna would be negatively charged with respect to the ground. The state of electrical “strain” in the space between the antenna and ground would likewise have reversed. If we can make these reversals rapidly and uniformly, the disturbance between the antenna and ground will be propagated away through space and this uniform disturbance we will call a radio or wire-less wave. It will have a vertical electrical vibration, and since motions of electrical fields are always accompanied by magnetic fields at right angles to them, it will have a

horizontal magnetic vibration. Since the radio wave consists of both electrical and magnetic vibrations we refer to it as an electromagnetic wave. You should note that the electric and magnetic vibrations are both at right angles to the direction of propagation of the wave.

The simplest guess as to the manner in which to produce the antenna charges rapidly and uniformly would be to use an alternating electric current. If one side of a circuit carrying alternating

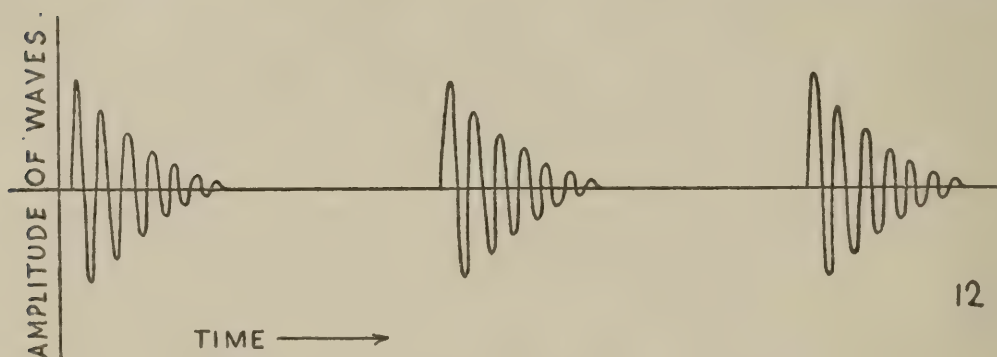


Fig. 12. Groups of Damped Wave Trains

current were attached to the ground and the other side to the antenna, the antenna would become alternately positive and negative with respect to the ground. In the early days of wireless telegraphy no method was known for producing steady alternating current at a sufficiently high frequency to be effective for wireless purposes.

Damped Waves. However, Lord Kelvin had shown mathematically that if a Leyden jar (a condenser made by coating a glass jar inside and out with tin-foil) were charged to a high electrical potential and then discharged between two small spheres, the discharge should be oscillatory. This prediction was made in 1853, and Fedderson, in 1857, showed that such would be the case. By referring to the picture of Hertz's early oscillator you will see that this is the device used for producing the rapid alternations of charge. Here two large metal plates were substituted for the coatings of the Leyden jar. Of course the alternations die out soon and a new set do not begin until

the condenser plates are again charged up by some source such as an "induction coil," or a high potential transformer. This process repeats from 25 to 500 times per second, according to the apparatus used. Transmitters using this means for obtaining their high frequency currents are called spark transmitters. The frequency of these waves is too high to be heard, but the signal from such a station gives rise to a tone whose frequency is determined by the number of *groups* of alternations that occur per second, and hence such devices are not suitable for carrying other sounds. Figure 12 represents the general form of the waves from a simple Hertz transmitter, but the form is somewhat different for a more complicated transmitter. A reference to damped wave trains is given at the end of this chapter.

Undamped Waves and Modulation. It was long known that the one essential thing for transmitting voice and music would be a radio wave which in itself would be silent. To produce such a wave a source of steady high frequency current was necessary. Alexanderson attempted to solve the problem by constructing an alternating current generator which would run at a phenomenally high speed. The Poulsen Arc as developed by the

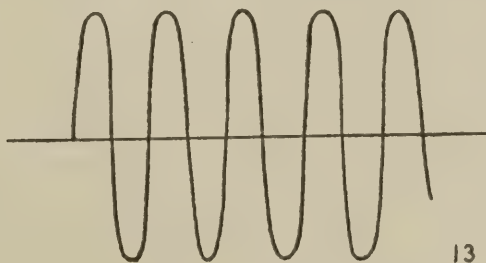


Fig. 13. *Steady Waves when Microphone Is Idle*

Federal Telegraph Company of San Francisco was one of the other famous attempts to obtain steady high frequency current. The final answer to the problem came with the development of the three electrode tubes now in common use in receiving sets, and the development of the circuits that go with them. By the proper use of these tubes and electric circuits it is possible to take electrical energy from direct current sources such as batteries and

to convert it into electrical energy manifested by alternating currents of almost any frequency up to 100,000,000 or more per second.

As has already been said the amount of this high frequency current which flows into the antenna is controlled by the amplified

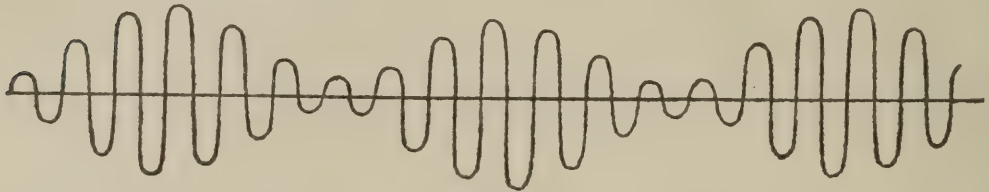


Fig. 14. Same Waves as those in Preceding Figure but Modulated by the Tones of a Tuning Fork

alternating currents that come from the microphone. It then follows that the variations in the *amount* of high frequency current reaching the antenna must follow the original vibrations of the sound striking the microphone. It is to be noted that the “modulation” of the high frequency current by the current of audible or voice frequencies is primarily to change the quantity of high frequency current flowing and not to change the frequency of this current. Actually some new high frequencies are created in the modulation process. If, for instance, the note *A* on the piano be played, we get, for standard pitch, a sound with frequency 435. A modulating current with frequency 435 is then created in the microphone.

If the high frequency current to be modulated has a frequency of 1,000,000 we will find after modulation that there are three high frequencies present, namely, 999,565, 1,000,435 and the original 1,000,000. It is not very evident why this should be true unless one goes through the mathematics of the electrical theory involved; but the mathematics predicts such a state of affairs, and experiment has verified it. If we have a great many frequencies in the modulating current, as would be the case in ordinary broadcasting, we would have a corresponding number of extra frequencies both above and below the original high frequency. These extra

frequencies are known as side bands. Since musical tones include frequencies up to about 5,000 per second it follows that a well-modulated wave from a station will contain a frequency band of about ten thousand in width, that is, about five thousand on either side of the original high frequency. The full width of these side

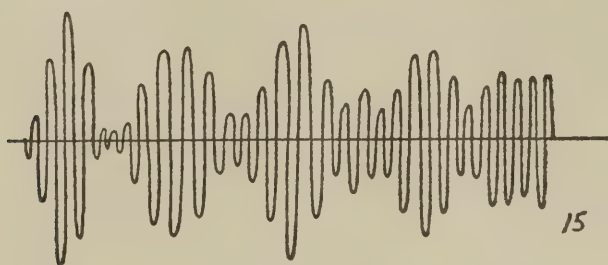


Fig. 15. Same Waves as Shown Before but Modulated by a More Complicated Sound

bands must be included by a receiving set if good quality is to be expected in the reproduction. This fact alone would dictate that broadcasting stations should not be licensed to operate closer than ten thousand in frequency. It also shows that frequency, not wave-length, is the thing to be considered when discussing the interference possibilities of one station on another. Of course, after the frequency has been determined, the wave-length can be calculated from the relation already given.

Propagation of Waves through Space. The electro-magnetic waves are propagated through space without the aid of material medium. This fact distinguishes the whole family of electro-magnetic waves from all other kinds of wave motion. Nevertheless the progress of these waves is influenced by any matter that happens to be in their path. Ordinary light can be refracted by passing from one medium to another. A familiar example of this fact is the passage of light from air through a prism of glass. The part of the radio waves near the ground is affected by the electrical conductivity of the ground. If the waves pass over sea water, the sea water, being a good conductor, tends to act as a guide to keep the waves curving about

we shall digress here to give a brief description of the tubes and their behavior, although later on in this series of lessons we shall return to the subject for a more detailed study.



Fig. 21. A Standard Detector Tube

Two Element Tube Detectors. In about 1883 Edison discovered that if a cold metal plate were sealed inside an ordinary electric lamp (in addition to [the regular filament]) current would flow through the galvanometer with one side connected to the cold plate as shown in the figure if the other

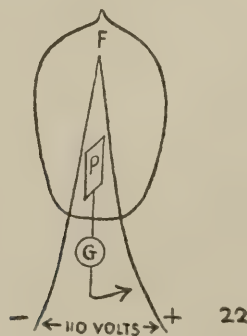


Fig. 22. The Edison Effect

side of the galvanometer were connected to the positive side of the filament, but no current would flow if it were connected to the negative side. The phenomenon was unexplained at the time, but in 1904 J. A. Fleming, an English scientist, developed the idea into a rectifier (or detector) for radio purposes.

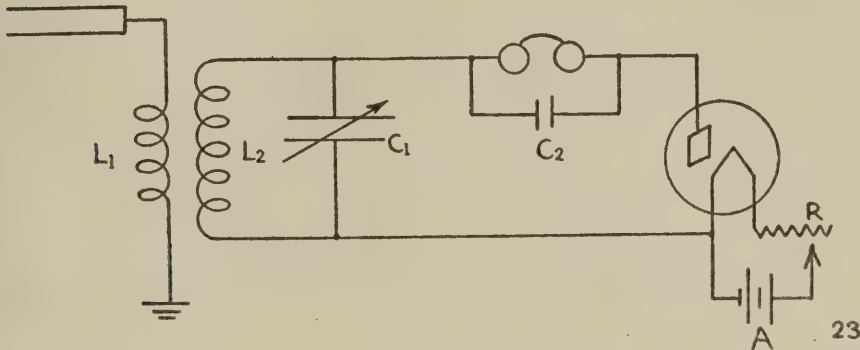


Fig. 23. Receiving Circuit Using a Fleming Valve in Place of a Crystal

Figure 23 shows the Fleming "Valve" in use in a circuit similar to one of the crystal circuits already shown. Of course a battery is necessary to supply current to keep the filament of the valve hot.

Three Element Tube Detectors. Before this time Richardson (in 1904) had shown by mathematical physics that when a metal is heated negative particles of electricity (which we call electrons) should evaporate from the metal somewhat as molecules of water are thrown off when water boils. This theory was much disputed until many experimenters by about 1912 had shown it to be correct. In the meantime the Fleming valve was developed for radio purposes, and in the hands of Lee De Forest, an American, it became a very sensitive detector. De Forest added a network of metal now known as a grid between the hot filament and the plate. (See Figure 24).

We shall not go far into the action of this type of tube in this introduction but shall discuss it further on. It is, however, evident

17 the electricity now attempting to flow through the telephone receiver would be indicated by a picture such as that of Figure 18. It is true that we would still have pulses of current and not a steady current, but these pulses would all be in the same direction and would therefore give an average effect as shown by the dotted line in the figure. If the incoming wave were unmodulated, the diaphragm of the receiver would be pulled in or out a bit and would remain there. But if the train of waves were modulated, the diaphragm of the receiver would move to and fro in accordance with the modulation and a sound similar to the original sound would be produced.

Simple Tuned Receiving Circuits. A receiver such as that just described would be extremely inefficient and not at all selective. By the proper use of coils (called inductances) and condensers it is possible to improve this circuit. The circuit is now called a tuned circuit because it responds to some one high frequency much more than to any other. This frequency (called the resonant frequency) can be changed by changing the value of either the inductance or the condenser or both. We are chiefly indebted to Sir Oliver Lodge, and in some degree to Senatore Marconi for the development of tuned receiving circuits. Lodge obtained a patent on tuning by adjustable inductance as early as 1897, while one of Marconi's most famous patents dealing with tuned circuits is dated 1900.

Figure 19 shows a simple tuned circuit, while Figure 20 shows a circuit which is called loose-coupled because the antenna circuit

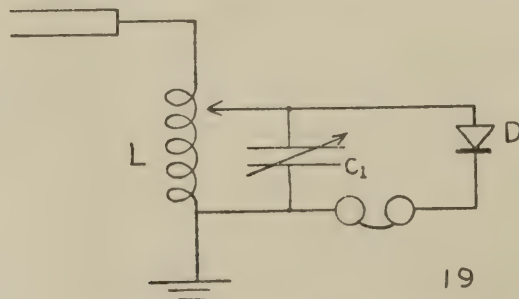


Fig. 19. Crystal Detector With Inductance and Variable Condenser Added for Tuning

is not connected directly to the detector circuit. "Coupling" is effected through the overlapping of the magnetic fields of the coils L_1 and L_2 . C is a variable condenser and D is the rectifier commonly called a detector.

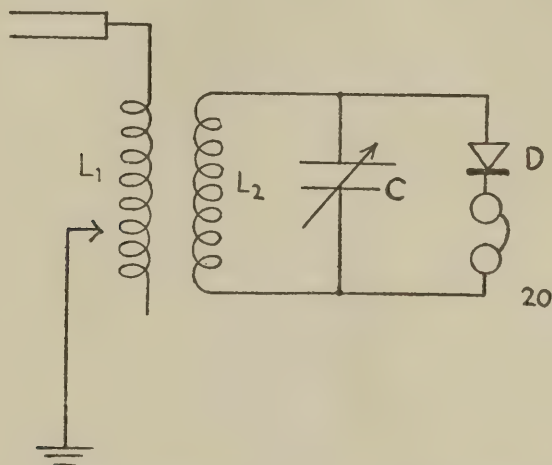


Fig. 20. Crystal Detector With the Tuning Improved by the Use of Two Inductances

Detectors. In the early days, the devices which permitted the flow of current in only one direction (and which we call detectors) were very imperfect, and much of the early improvement in distant reception of telegraph signals came about not so much with increased power in the transmitters as with improvements in the detectors. The simplest of detectors now in common use is known as a crystal detector. It may consist of a contact between metal, such as brass or gold, and a crystal such as silicon, or galena, or it may be a contact between two different kinds of crystals. We shall not be concerned here with the reasons why such a device should rectify, but be content with the experimental fact that it does.

The detector in most common use today is the three electrode tube which gives some amplification at the same time that it detects. The tube detector may be inserted in the simple crystal receiver circuits shown instead of the crystal, or, as is usually the case, it may be used in a more complicated circuit. The use of these tubes has become so general in present day radio that

we shall digress here to give a brief description of the tubes and their behavior, although later on in this series of lessons we shall return to the subject for a more detailed study.



Fig. 21. A Standard Detector Tube

Two Element Tube Detectors. In about 1883 Edison discovered that if a cold metal plate were sealed inside an ordinary electric lamp (in addition to [the regular filament]) current would flow through the galvanometer with one side connected to the cold plate as shown in the figure if the other

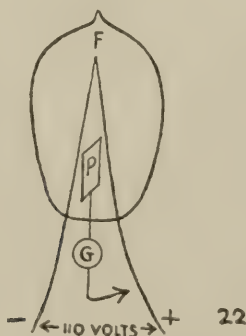


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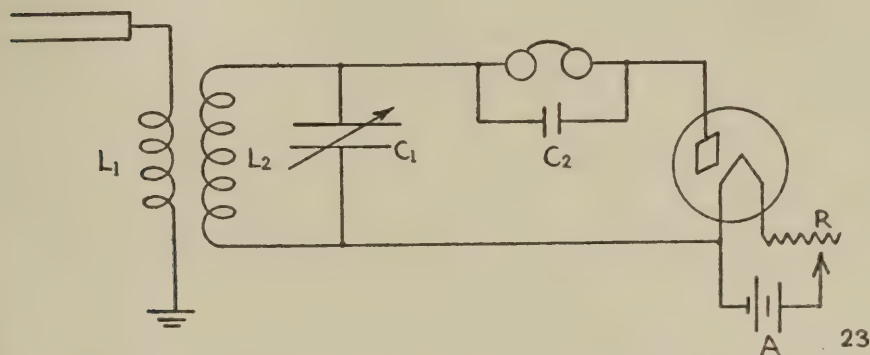


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Three Element Tube Detectors. Before this time Richardson (in 1904) had shown by mathematical physics that when a metal is heated negative particles of electricity (which we call electrons) should evaporate from the metal somewhat as molecules of water are thrown off when water boils. This theory was much disputed until many experimenters by about 1912 had shown it to be correct. In the meantime the Fleming valve was developed for radio purposes, and in the hands of Lee De Forest, an American, it became a very sensitive detector. De Forest added a network of metal now known as a grid between the hot filament and the plate. (See Figure 24).

We shall not go far into the action of this type of tube in this introduction but shall discuss it further on. It is, however, evident

that if the potential of the grid of this tube with respect to the filament be varied, it will effect the flow of electrons to the plate. When the potential of the grid stays constant, a steady flow of electrons is maintained by means of the battery called a "B" battery. Consequently there will be variations in the current that flows

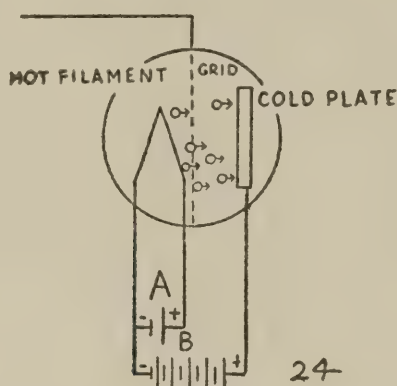


Fig. 24. Three Electrode Tube as Developed by DeForest

through the telephones and these will correspond to the average variations in potential of the grid due to the incoming signal. (See

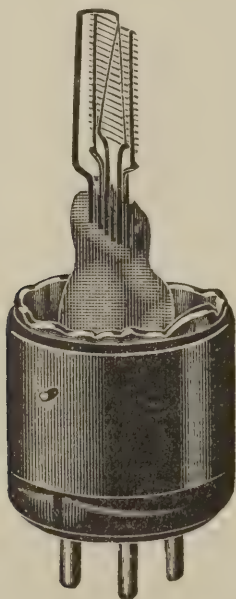


Fig. 25. Inside of a Tube showing Filament and Grid

figure 26.) In the case of crystal detectors, all of the energy that produces motion of the diaphragm of the telephone receivers comes from the train of radio waves. But with the tube detector the radio waves serve merely as a control to vary the amount of electrical energy that comes from local batteries. It is not surprising then

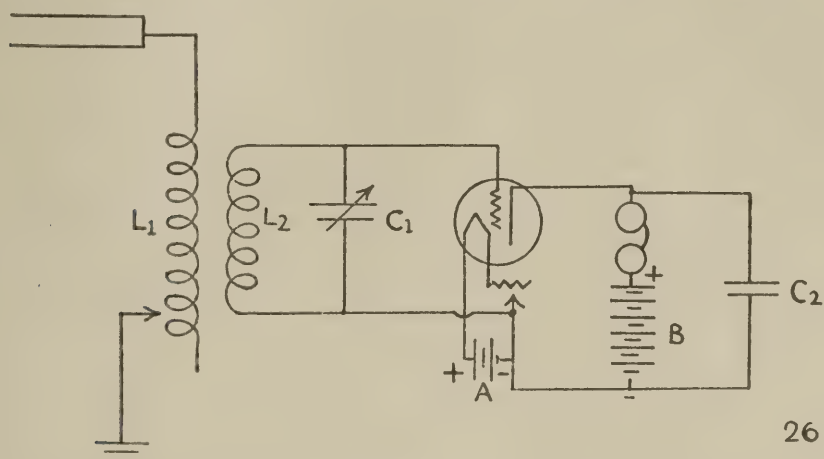


Fig. 26. A Simple Receiving Circuit Using a Tube Instead of a Crystal for a Detector

that the amount of volume from a tube detector is much greater than that obtainable from a crystal receiver.

Figure 26 shows a three electrode tube such as that described above connected to the fundamental circuit of Figure 20 where

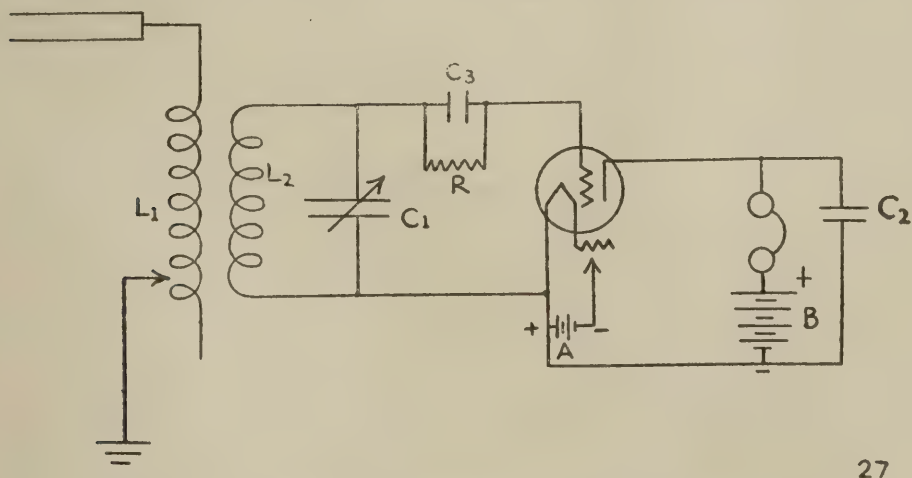


Fig. 27. A Simple Tube Receiving Circuit to Which a Grid Condenser and Leak Have Been Added

a crystal was used. Figure 27 shows the same circuit except that a so-called grid condenser and a grid leak have been added. This latter method is the one in more common use today and we shall analyze both in a later chapter.

Regenerative Detector. The science of radio received a great forward impetus in 1912 when E. W. Armstrong discovered and applied the principle of regeneration. This principle is apparent if we consider the receiving circuit shown in Figure 28. A variation of grid potential results in a change of plate current in this circuit just as in those of Figures 26 and 27. But the plate circuit contains a coil which is placed near the coil in the grid circuit. We shall later see that according to well-known laws of magnetism variations in the current of one of these coils induces electrical potentials across the terminals of the other coil. So the changes in current in the plate coil cause potential variations in the grid coil, and since there is no appreciable amount of time involved in this process, these potential changes occur in step with the original changes that came as a result of the wireless wave and made the original variation in plate current. Hence the amount of change in the plate current is greater than it would have been had not energy been fed back into the grid circuit. If the plate coil, T, (called a tickler coil or feed back coil) be too large or be placed too close to the grid coil, the amount of energy fed back will more than overcome the resistance of the various parts of the circuit and the variations

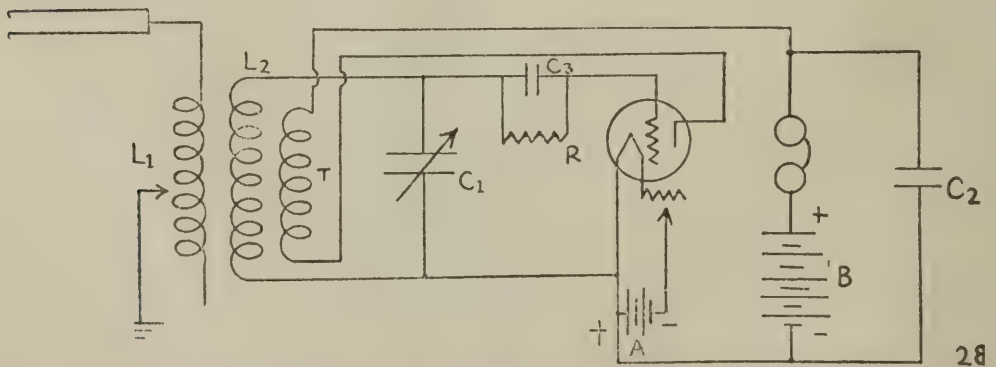


Fig. 28. Regenerative Receiving Circuit

of the current will be self-sustained without longer depending on, or following, the impulses that come from the antenna circuit. The circuit is now said to be oscillating. This scheme is the nucleus of the idea that has been developed for the generation of high frequency currents for broadcasting stations. If, however, receiving circuits are operated in the oscillatory condition, the quality of the received signal is badly distorted. Moreover, the set behaves as a miniature transmitter and serves to annoy other listeners sometimes up to distances of ten to twelve miles.

When the set is properly operated it is an exceedingly efficient receiver. Considerable skill is required for efficient operation of this receiver, and this fact, combined with its tendency to annoy other listeners, has led to the development of more elaborate and more dependable types of receivers. There are two principal types of receivers now before the public. One is a rather complicated sort of circuit called a superheterodyne. The invention of this circuit is another of those to be credited to Armstrong. The other type of circuit now popular is a circuit in which the feeble signal current from the antenna is amplified at the original high frequency by tubes so connected as not to do rectifying (detecting). After the feeble signal is built up to moderate strength by passing through two or more amplifying circuits and tubes it comes to a tube arranged for detecting usually without regenerating. There are

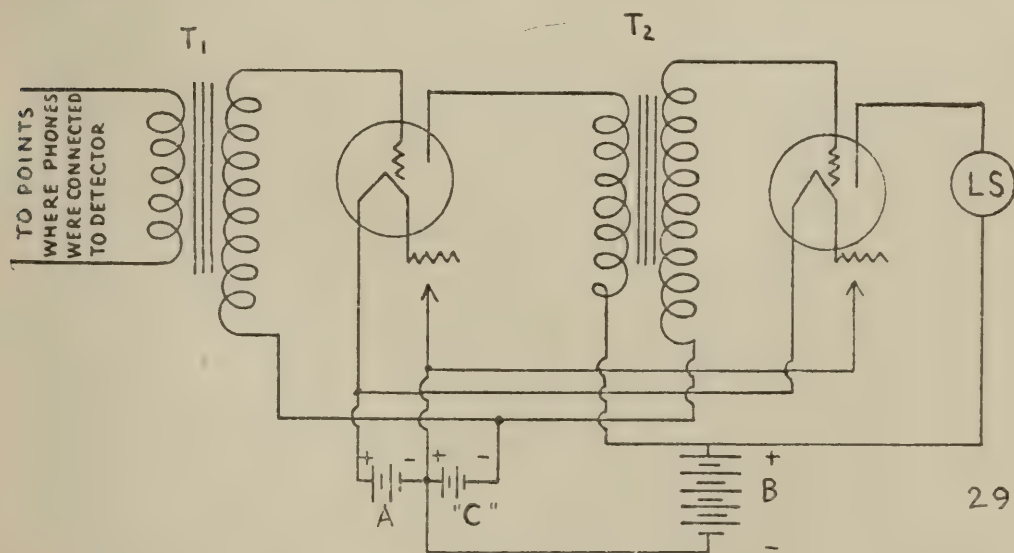


Fig. 29. Two Tube Amplifier With Transformer Coupling

many modifications of this type of circuit. Neutrodyne and "Tuned Radio Frequency" receivers are the largest members of this class. We shall discuss their problems at length later on.

Audio Amplification. So far we have considered listening to signals only by telephone receivers. If we wish to increase the volume of sound sufficiently to fill a room we find ourselves confronting the rather large problem of taking the feeble signal currents from the detector and amplifying them the necessary amount without introducing distortions. In all of the power work in ordinary electrical engineering only one frequency of current is dealt with at a time and new motors, transformers, and what-nots are made for each different frequency of commercial alternating currents. But when we amplify sound signals we are dealing with currents whose frequency of alternation may be as low as 20 per second, and at the same time we will have currents with frequencies as high as 4,000 or possibly 5,000. It is a difficult task to make an amplifier which will handle all of these frequencies uniformly well. The most common method now employed is to use tubes coupled together with transformers as shown in Figure 29. The transformers consist, as shown, of two

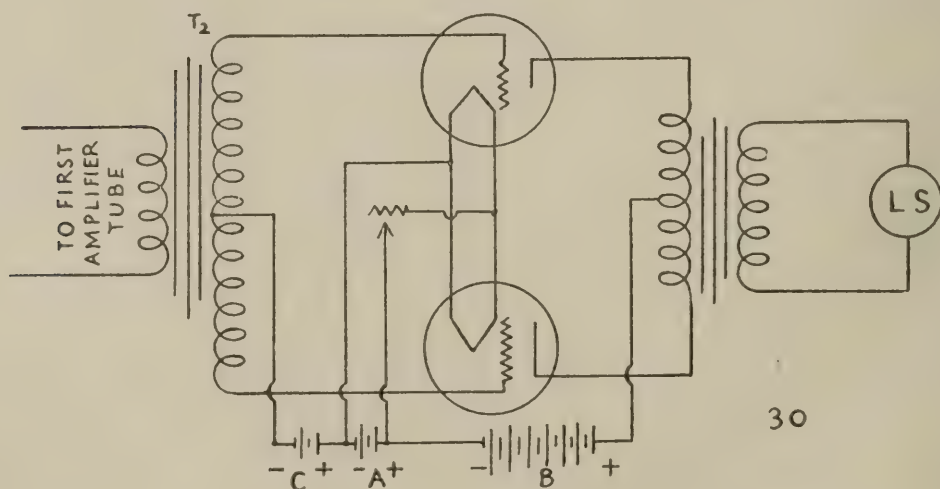


Fig. 30. A "Push-Pull" Amplifier Stage. The output of transformer T_2 is here divided between two tubes

windings wrapped on an iron or soft steel core. Little if any distortion occurs in the tubes themselves, but a great deal of distortion occurs in the transformers unless they are very carefully made. If the amount of amplification is too great, the potential variations of the grid of the last tube may be greater than can be followed by the plate current of this tube. When this is the case, great volume is obtained from the loud speaker, but the quality is extremely bad. To avoid this distortion and still keep the large volume a method of dividing the potential changes of the last transformer between two tubes has been devised. The changing plate currents of both these tubes are made to pass through the primary winding of an additional transformer. In this manner the current from the "B" battery is kept out of the loud speaker, but the changes of this current due to both the last tubes give rise to large alternating potentials across the terminals of the output winding of the last transformer. This method of dividing the input potential between two tubes and then combining the output of the tubes is known as push-pull amplification.

Two other types of coupling for amplifier tubes, methods which succumbed to the greater efficiency of transformer coupling in the days of wireless telegraphy and early radio broadcasting, have been revived and are now in extensive use due to the fact that it is easier to obtain uniform amplification with these methods than with transformers. Since these two types of coupling are less efficient than transformer coupling it is necessary to use tubes having a greater amplifying characteristic or else to use more tubes than would be necessary with transformer coupling. The two types are known as resistance coupled and impedance coupled. They will be discussed at length in a later section. The great increase in the use of these types of amplification is a strong indication of the trend of the attitude of the public in general towards the whole field of radio. At first radio was a novelty to the masses. There was a certain amount of exhilaration attached to the game of trying to listen to stations from one to three thousand miles away. The listener was concerned with little outside of being able to hear the announcer plainly enough to get his station's call letters. The idea of listening either critically or for enjoyment to the music of the radio as one might do at a concert or even in listening to

a Victrola record was almost entirely absent. But now the radio has completely lost its position as a novelty, and even its position as an amusement has given way to its greater calling as a dependable and necessary adjunct to life in the twentieth century. Already we are so accustomed to having good dinner music in our homes, to having the best of jazz music almost at any time we want it, to getting weather reports and sport news, not to mention business reports, to listening to symphony concerts from the great music centers of the country, and even to listening to the public addresses of the President of the United States, that it is hard to believe that we were ever without the radio.

To meet this increased demand for quality reproduction, manufacturers of transformers have improved their products greatly in the last few years, so that this type of coupling bids fair to hold its own with the other two types.

Loud Speakers. Another result of the demand for quality has been the great improvement in loud speakers during the last two or three years. At the present moment the speakers of the cone type, on the average, seem to be somewhat better than those employing horns. Needless to say, the success of the better cone speakers has resulted in a flooding of the market by cheap cones which are, in general, greatly inferior to the four or five best ones now on the market. There is still plenty of room for improvement in loud speakers.

Many people fail to get the best quality possible from their speakers because they operate their sets too loudly. If distortions occur in the amplifier, it is hardly fair to blame the speaker for the bad quality. Greater volume means of course that greater energy must be supplied to the speaker. If the ordinary type of amplifier tube be used, sufficient undistorted energy can not possibly be supplied to the speaker to give the volume that we sometimes demand. To meet this difficulty "power" tubes have been developed for use in the last stage of amplifiers in order that sufficient energy may be fed to the speaker to operate it properly. In general these tubes take larger "B" batteries than

we have been accustomed to use in the past. But the continued response of the public to these increased expenditures is still further proof of the statement that radio has passed from the novelty stage to a useful and an essential place in our present day civilization.

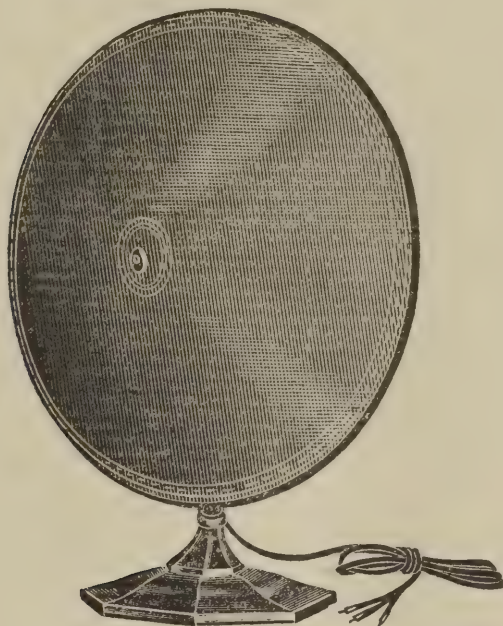


Fig. 31. A Cone Type Speaker

Chapter I—References

Suggested references for those who wish to make a more extended study of the subjects discussed in this chapter.

A more extended introduction to the subject.

Radio-Phone Receiving—Published by VAN NOSTRAND.
Entire book.

History and Nature of Electro Magnetic Waves.

Elements of Radio Communication—STONE.

The Principles Underlying Radio Communication—SIGNAL
CORPS, U. S. ARMY. Chap. IV.

Damped Waves.

Radio Engineering Principles—Lauer and Brown. Chap. IV.

The Nature of Sound.

The Science of Musical Sounds—D. C. MILLER. Entire
book.

For a strictly technical and mathematical discussion of Electro-Magnetic Waves consult:

Principles of Wireless Telegraphy—PIERCE.

Wireless Telegraphy—ZENNECK.

Electro-Magnetic Theory—HEAVISIDE.

FUNDAMENTAL ELECTRICAL
THEORY

TOPICAL INDEX

CHAPTER II

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 Current Electricity
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CHAPTER II

Fundamental Electrical Theory

The Nature of Electricity. If we are to consider the problems of radio set construction in an intelligent manner it will be necessary to have in mind some fundamental notions concerning the nature and behavior of electricity. Science has not yet given a precise or complete answer to the question, "What is electricity," but many things useful for our purposes have been discovered. One of the startling conceptions of the present day is that all matter is electricity. The chemists and physicists of the last century established the idea of matter being made up of atoms. Atoms were defined as the smallest particles into which a substance could be divided even by chemical means. Finally even the mass of the atoms of each of the elements was determined. One of the next great problems of physicists and chemists was to attempt to describe the construction of individual atoms. To attack this problem the scientists must have most wonderful imaginations; but in addition, it is necessary for them to have the training and skill which will enable them to devise and carry out experiments to prove the truth or falsity of their theories. We have now reached a state in the development of radio long ago attained in pure science. We can no longer have two classes of worker, one called a theoretical man, and the other a practical man. For the theoretical man who never puts his theories to the test seldom produces theories of any value, and the "practical" man who knows no theory seldom knows enough to develop anything that is really practical.

The best evidence today would lead us to believe that every atom is made up of positive and negative particles of electricity

normally present in equal numbers so that the atom as a whole is said to be neutral. Even the mass of the atom is due to these particles of electricity. In other words, an atom is not a chunk of something with charges of electricity stuck on it; but rather, it is nothing but the charges of electricity. The atoms of one

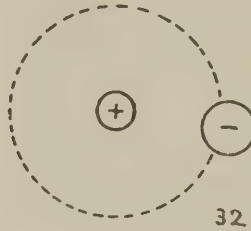


Fig. 32.

Hydrogen Atom. The negative electron is thought to revolve around the positive "proton," as indicated by the dotted path

element differ from those of another only in the number and arrangement of the positive and negative electric charges. The simplest atom is that of hydrogen and might be represented by Figure 32. It has one positive charge and one negative charge. These charges are separated by a distance that is large in comparison with the sizes of the electric particles themselves. Moreover we believe that the electron revolves about the positive particle—somewhat as the earth and other planets revolve about

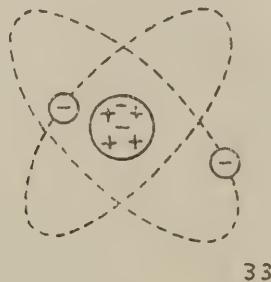


Fig. 33.

Helium Atom. The nucleus contains 4 protons and 2 electrons. The orbits of the two external electrons may possibly be represented by the dotted lines

the sun. The element next heavier than hydrogen is helium. It seems to have four positive particles and two negative particles in its nucleus with two other negative particles separated from the nucleus as shown in Figure 33. If we continue through the elements in the order of the weight of their atoms we come to carbon in the sixth place. It seems to have 12 positive and 6 negative charges in its nucleus and 6 more negative charges in its external orbits. We find nickel in the 28th place with either 58 positive and 30 negative charges or 60 positive and 32 negative charges in the nucleus and 28 electrons scattered about in various orbits. These rather fantastic conceptions of atoms of matter have been built up as the result of careful experimenting and keen mathematical calculation. They may not be absolutely correct in every detail; but if we keep these notions of atomic structure in mind we will be able to think more clearly as we proceed in the study of electricity.

It is not at all difficult to remove an occasional electron from the external part of an atom. In fact, if we rub a piece of cat's fur over a slab of hard rubber, some of the electrons that belong to atoms of the fur stick to the rubber and we say that the rubber is negatively charged. We say that the cat's fur is at the same time positively charged, not because it has gained any positive electricity but because it originally had equal amounts of both positive and negative and has now lost some of its negative electricity. This is the modern explanation of frictional electricity. Frictional electricity was first reported by Thales of Miletus who rubbed amber with silk. This was about 600 B. C. And yet it was not until the present time with our modern theory of atomic structure that a good explanation of the phenomenon was made.

Behavior of Electricity. But long before much was known as to the nature of electricity, a great deal was learned about its behavior by the simple process of doing experiments with it. The laws of behavior so discovered are valuable to us regardless of the fundamental nature of electricity.

The most elementary law is that two charges of electricity attract one another if one is positive and the other negative, but

that they repel one another if they are both positive or both negative. This force of attraction or repulsion falls off as the distance between the charges increases, but at a greater rate than the rate of change of the distance. We can express this law algebraically thus:

$$F = \frac{q_1 q_2}{d^2}$$

where F is the force, q_1 and q_2 the charges, and d the distance.

For an example consider the case where one of the charges is positive and the other negative. Then a third charge placed in the vicinity of these charges would be attracted by one of them and repelled by the other. Any point in the vicinity of one or more charges is said to be situated in an electric field of force. The intensity of the field depends on the charges and their positions with respect to the point. It can be measured by placing a charge of known amount at the point and observing the force on it.

Most of our practical laws of electrical circuits were discovered before much was known about the actual nature of electricity and hence rather arbitrary units for the various electrical quantities were chosen. The practical unit of quantity of electricity is called a coulomb. We now know that it takes 6.28 million million electrons to make this much electricity. A coulomb is not really a very large amount—but an electron is a very tiny amount.

Potential. Let us suppose that we have a small object such as a brass sphere and that to begin with there is no charge on it. Let us bring up electrons from a considerable distance and put them on the sphere. At first it will require almost no effort to bring up these charges, but soon we will find that the electrons already placed on the sphere are trying to repel the next ones that we bring up. So we have to do work against this repulsive force in order to place more electrons on the sphere. The more we get on the harder it becomes to place more on. We now say that the sphere is at a different electrical potential than the distant surroundings. We are never interested in absolute values of potential

but only in potential differences. For simplicity, however, we assume the earth to be at zero potential, and so we call the difference of potential between the earth and the object in which we are interested, the absolute potential of the object. It is the work that would be done in bringing unit quantity (a coulomb) of electricity from the region of zero potential up to the charged body.

The practical unit for potential difference is the volt. We might define it by saying that two points have a difference of potential of one volt if it requires one joule of work to carry a coulomb of electricity from one point to the other. (A joule is a small unit of work. In terms of our electric light bills it is one watt second, i. e., one kilowatt hour divided by 3,600,000).

Capacity. We find that the difficulty experienced in placing more charge on a body already charged depends not only on the amount of the charge but also on the shape of the body and the presence of objects near the body. The ratio between the quantity of electricity placed on an object and its potential is called the capacity of the object.

$$C = \frac{Q}{V}$$

Hence we see that any object made of conducting material has capacity. If the object is constructed so that by virtue of its size or shape it may be made to hold appreciable quantities of electricity without attaining unreasonably large potentials, it is called a condenser. The most simple type of condenser is made by using two plane metal sheets placed near one another. The presence of either plate increases the "capacity" of the other. The capacity of such a system can be increased by

Using larger plates,

Putting the plates closer together,

Putting glass, mica, or other non-conductors between the plates,

Increasing the number of plates and connecting alternate ones together. This type is known as a parallel plate condenser.

Parallel plate condensers with air between the plates constitute a commonly used type for radio purposes largely because they lend themselves easily to giving adjustable values of capacity. One set of plates is usually held rigid, and the other set mounted on an axis rod. When this rod is turned, a greater or less amount

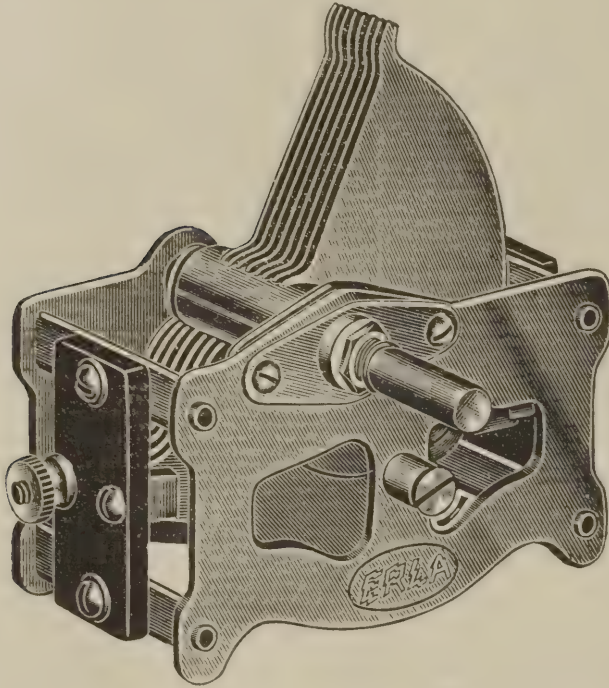


Fig. 34. Air Condensers

of the moveable (or “rotor”) plates is made to mesh with the “stator” plates.

Where condensers of fixed value are desired, it is customary to separate pieces of tin foil with mica. Such a combination can be rolled up and put in very small space. Paraffined or waxed

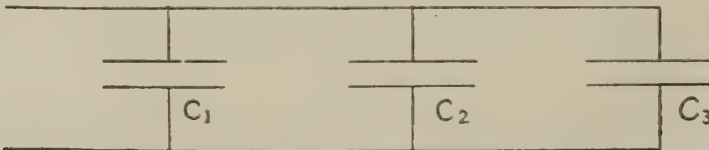


Fig. 35. Three Condensers Connected in Parallel

papers of various kinds are commonly used in place of the more expensive mica.

Elementary considerations of electricity lead us to two important laws for the use of condensers in combination. When condensers are connected in parallel (see Figure 35) their capacities are added.

$$C = C_1 + C_2 + C_3 \text{ etc.}$$

Where C is the total capacity and C_1, C_2, C_3 , etc., the individual capacities. But when they are connected in series (Figure 36) the overall capacity is reduced. The value is given by this relation

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \text{ etc.}$$

For two condensers this expression reduces to

$$C = \frac{C_1 C_2}{C_1 + C_2}$$

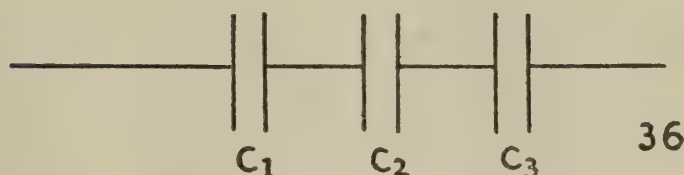


Fig. 36. Three Condensers Connected in Series

Hence if we have two equal condensers hooked in series, the overall capacity is only one-half the value of a single condenser. If a large and a small condenser be hooked in series, the overall capacity is always less than the value of the *smaller* condenser.

The unit of capacity in the practical system (called a farad) is defined as the capacity of a condenser whose potential difference between plates is one volt when the quantity of charge put on the condenser is one coulomb. A condenser with a capacity of one farad would be an enormous condenser. For ordinary purposes we take one millionth of this value as our unit and call it a microfarad. Many of the condensers with which we are concerned in

radio work have capacities so small that even this unit seems large and so we speak of a milli-micro-farad and a micro-micro-farad for one thousandth and one millionth of a micro-farad. The size of condenser ordinarily used for tuning in a radio circuit may be said to have a capacity of about

.0005 micro-farads
or .5 milli-micro-farads
or 500. micro-micro-farads

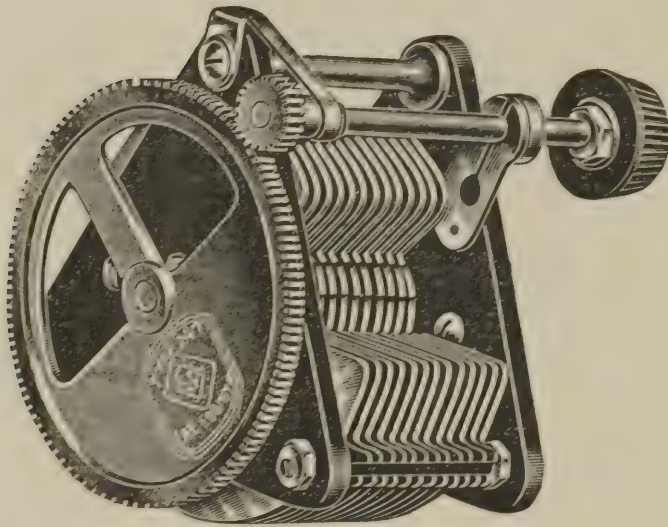


Fig. 34a. Air Condenser with Vernier Attachment

Current Electricity. If we permit charges of electricity to move from one point to another, we say that we have “current” and the unit of current is the ampere. An ampere is the amount of current when one coulomb passes a point in the path of the current every second. Some of the currents in radio sets are very small and we therefore speak of milliamperes and micro-amperes for thousandths or millionths of an ampere.

Metallic Conduction. Let us consider a copper wire in the light of the theory of atomic structure outlined at the

beginning of this chapter. If we imagine that a part of the wire could be magnified so that we could see the atoms and their electrons we might represent a small part of the wire by the drawing in Figure 37. The circles indicate the boundaries within which the electrons belonging to each atom are sup-

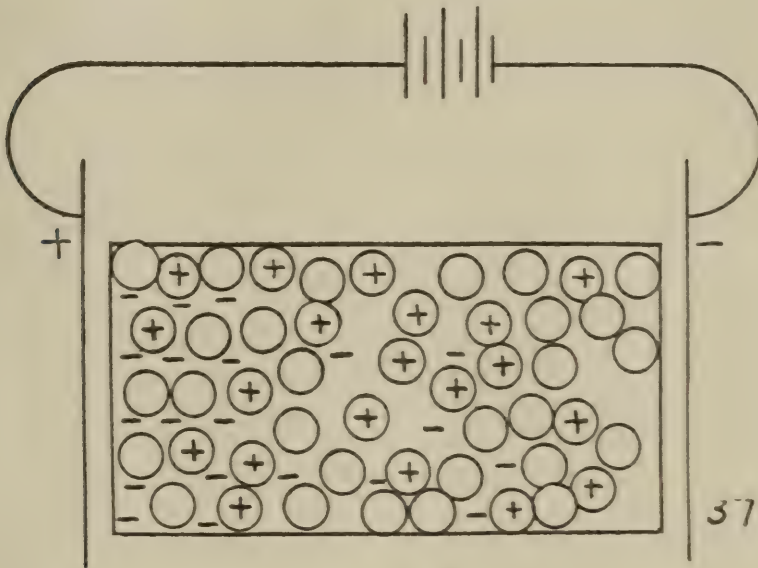


Fig. 37. An imaginary and greatly magnified view of a conductor showing that the "free" electrons of the conductor travel towards the positive part of an electric field. The circles represent the atoms making up the conductor and the dashes the free electrons

posed to stay. Note that there is a considerable number of electrons floating about in the spaces between the atoms. Each one belongs to an atom somewhere in the wire, but has succeeded in breaking away from the attraction of the nucleus. If it accidentally gets too near some other atom that has lost an electron it is likely to be drawn in to that atom and become a part of it. Suppose now that a potential difference be established (by methods that we shall discuss a little further on) between the ends of the wire as shown in Figure 37. Then these electrons in the wire will find themselves in an electric field of force and will start traveling from the negative towards the positive part of the field according to the laws of attraction and repulsion that we have already dis-

cussed. This drifting of the electrons constitutes a flow of current in the solid copper wire. We have no motion of positive electricity in this case for all the positive electricity is held in the relatively stationary atoms. The flow of electrons soon stops if the arrangement is as shown in Figure 37 with an excess of electrons at one end and a deficiency at the other. If there is a metallic contact between that part of the circuit which gave rise to the electric field in the first place, we may have a steady current with electrons entering the wire at one end and leaving at the other.

Heating Effects. When we add a general movement of the "free" electrons to their general drifting we cause them to strike atoms more violently than before. The tendency of the atoms to vibrate is thereby increased, and it is in this manner that the conductor becomes heated. Theory would lead one to believe, and experiment shows it to be true, that if you double the rate of flow through the wire you multiply the heating effect by four. That is, the heating effect is proportional to the square of the current through a given conductor. The rate at which heat is developed is given by

$$H = I^2 R$$

where I is the current and R is the resistance of the conductor. We shall discuss resistance still further in a later paragraph.

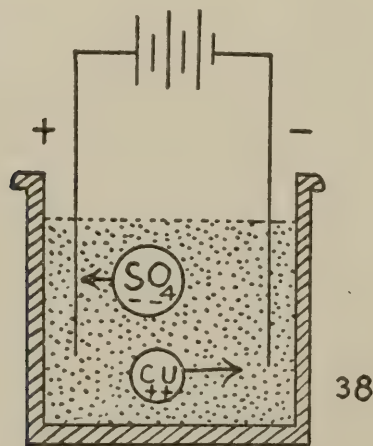


Fig. 38. A Copper Sulphate Cell with the Motion of the Ions Indicated

Chemical Effects. The molecules of many substances split up when they are dissolved in water. For a simple case consider copper sulphate. When it is put into water, the copper atom breaks away from the sulphate molecule leaving the sulphate molecule to drift by itself. The most interesting feature of this separation is that the sulphate molecule steals two electrons from the copper atom at the time of separation. The copper atom is now said to be positively charged (because it would be electrically neutral if it had not lost the electrons), and the sulphate molecule is, of course, negatively charged. Atoms thus charged are called *ions*.

If two electrodes connected to a source of supply of electricity are placed in a copper sulphate solution, these ions will find themselves in an electric field of force and will start moving, the positive copper ions towards the negative electrode and the negative sulphate ions towards the positive electrode. If the latter happens to be copper, the sulphate ions will attack it and pull copper atoms from the electrode into the solution. The copper ions that go to the negative electrode will tend to stick to that electrode. This is the manner in which electroplating is done. In actual practice it is very necessary to have the negative electrode extremely clean if the plated metal is expected to stick tightly.

Velocity of Ions. It is interesting to note that while the effects of the flow of electricity are felt almost instantly (approximately the speed of light) along a conductor, yet the actual drift of the electric charges in the direction of the electric field is quite slow. In a copper wire carrying a normal load, the drift of electrons is a small fraction of a centimeter per second. The motion of the ions in a solution is still slower. We should point out that in the case of electrons passing through a wire, many of them doubtless collide with atoms so violently that they stay in the atoms and other electrons become free and travel on.

We have every reason for supposing that the free electrons are always darting to and fro at speeds high in comparison with the general drift that constitutes current.

Magnetism and Electricity. We have discussed heating effects and chemical effects of current in a brief fashion, and we now must consider another extremely important effect. In the year 1819, the Danish physicist Oersted discovered that if an ordinary magnetic compass were placed near a wire carrying current, the compass needle would be deflected from a north and south position and tend to set itself at right

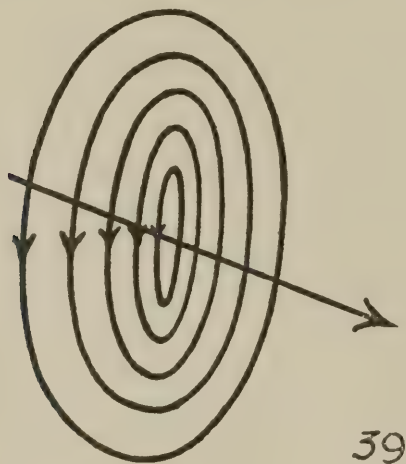


Fig. 39. A Magnetic Field Exists Around a Conductor Carrying Current

angles to the wire. This was the first definite evidence of any relation between electricity and magnetism. Oersted made known his discovery to the world and soon Ampere and Faraday and other scientists of the first half of the nineteenth century were busy finding all the secrets of electro-dynamics on which our whole commercial power industry now is built.

Our first effect of electro-dynamics, then, is that when a current is flowing, there exists a magnetic field around the current and at right angles to it. This effect may be used to define the amount of current flowing. The unit so arrived at has a rather large value, and the unit called an ampere, which we have already defined, is just one tenth of the unit obtained by this magnetic definition.

Production of Electricity—Magnetic Method. Another extremely important fact of electro-dynamics is that

if a conductor of electricity be moved across a magnetic field, the free electrons in the conductor tend to move, and if the conductor be closed back on itself through an external circuit we will have a flow of electrons throughout the circuit. If we define

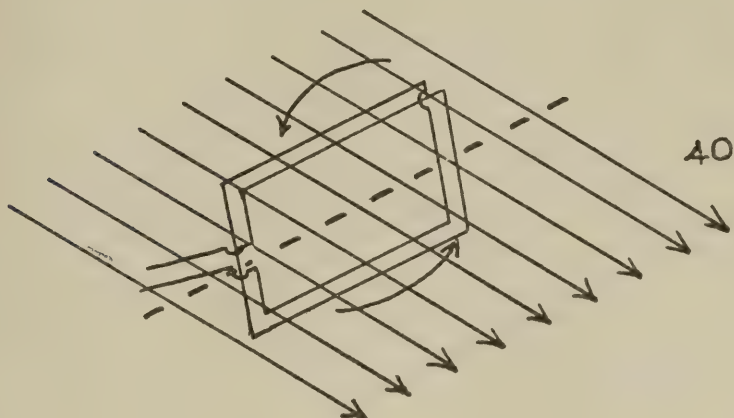


Fig. 40. A Coil of Wire Rotating in a Magnetic Field

magnetic flux as the product of magnetic field strength and the area across which the field exists, we can say that if we have a closed conductor we get an “induced” current in the conductor whenever we change the amount of magnetic flux included in the circuit. We might change the flux by bringing up bar magnets or removing them, or by bringing up coils of wire in which current from some other source is flowing, or by stopping and starting currents in nearby coils without bothering to move them. The most commonly used method is to have a stationary magnetic field obtained by passing current through coils wrapped on iron cores. Copper conductors are then moved in this stationary field.

It must be evident to the reader that the direction of flow of electrons in the wire will depend on the relative direction of the magnetic field and the motion of the conductor. If a coil of wire be rotated about an axis through its own plane (see Figure 40), then with respect to the output terminals of the coil as shown in the figure the electrons will tend to flow in one direction and then in the reverse direction as the coil continues around. These reversals are smooth rather than abrupt. We might represent the flow of

electrons by the diagram of Figure 41, where all the curved line above the horizontal line represents flow in one direction and that below the line, flow in the other direction. We have then described a simple form of alternator, or generator of alternating current. This is the kind of current that is usually supplied for domestic

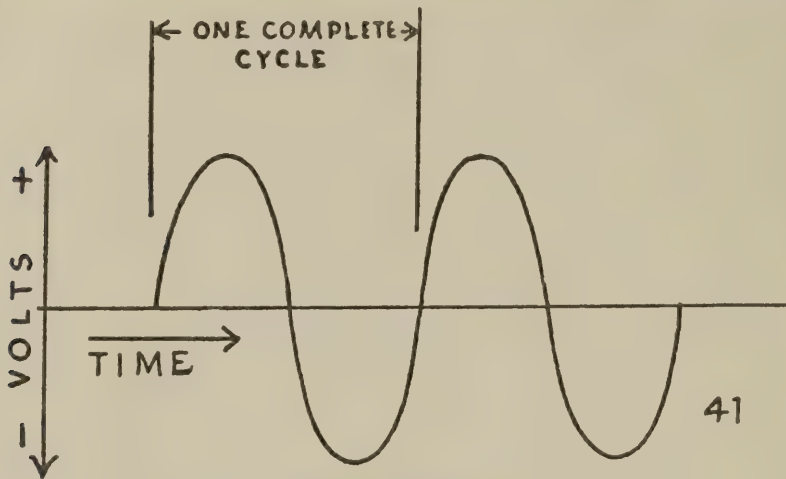


Fig. 41. Simple Alternating E. M. F.

purposes by power companies. The rate of alternation varies in different localities. The two most commonly used rates are 60 and 25 complete "cycles" per second. (A complete cycle is the flow in one direction and also the reverse flow).

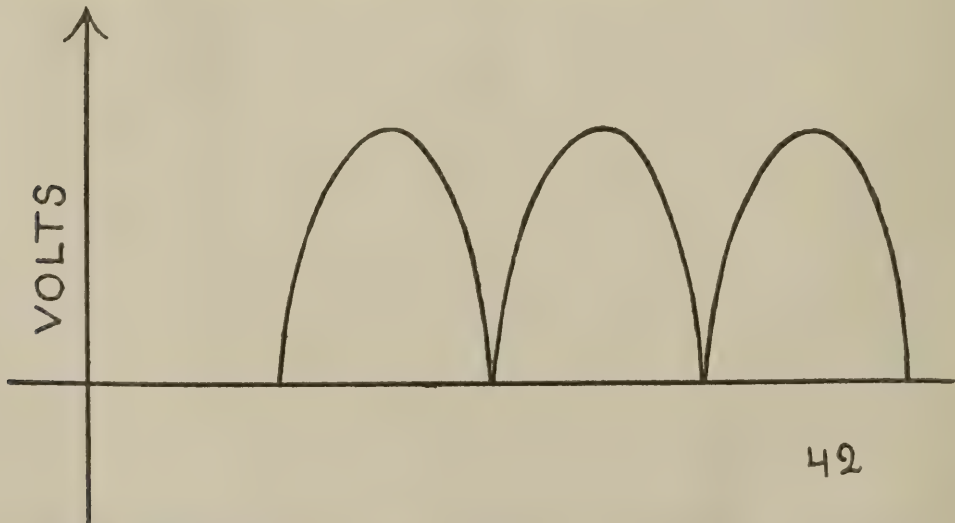


Fig. 42. E. M. F. From a Simple Alternator when the terminals of the coil have been attached to a commutator

If it is desired to produce direct (or steady) current by magnetic means, an automatic reversing switch (called a commutator), is arranged on the shaft that revolves the coils of wire. It is evident from Figure 42 that this arrangement produces pulsating rather than steady current. If it is desired to make the current fairly

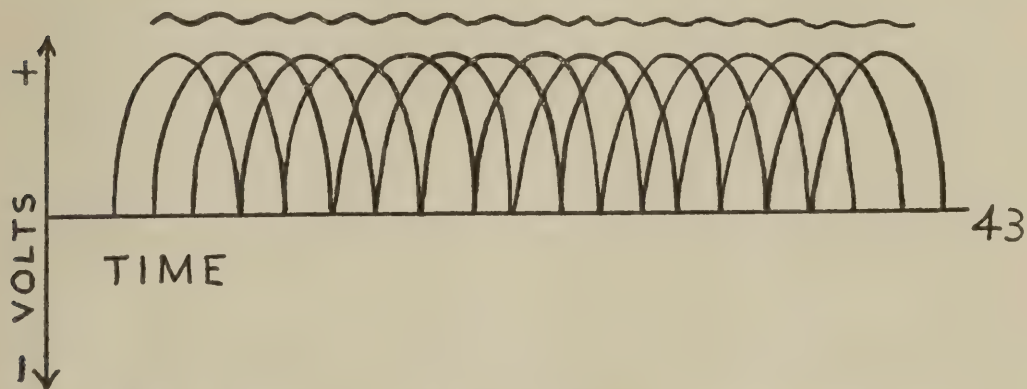


Fig. 43. E. M. F.s from a Direct Current Generator. The top line shows that the e. m. f. is not quite steady

steady, a number of coils are arranged on the same shaft so that their maximum induced electro motive forces occur at different times, and the number of magnet cores producing the stationary field of the generator is also increased. We then get an effect as shown in Figure 43. It is evident that even this current is not strictly steady, and in fact, it will produce a humming effect in a pair of telephone receivers. A direct current generator is often called a dynamo and an alternating current generator simply an alternator.

Most of the electricity produced in the world is produced by means of either dynamos or alternators such as those described. Note that these machines do not *make* any electricity but simply pump through conductors free electrons that are already present in the conductors.

Production of Electricity—Batteries. The other great means of obtaining electricity is, of course, by means of batteries. Batteries are principally of two kinds:

First. A type that maintains two electrodes at a difference of potential while electrons flow between these electrodes

through an external circuit. The energy is supplied by chemical action which finally becomes exhausted and the current ceases until the chemicals are renewed.

Second. A type similar to the first except that the chemical actions causing the flow of electricity can be easily reversed by forcing a flow of electricity through the battery in the opposite direction to that originally occurring.

To one who is familiar with chemistry it will be evident that there is no sharp line between these two types of batteries. That is to say, some batteries can be made whose chemical action can be reversed by the process described but not efficiently.

Primary Cells. Of the first type of battery, the two in most common use are the crow's foot battery and the dry cell. The "crow's" foot is named from the shape of the zinc electrode. This electrode is placed in the bottom of the cell and covered with a dilute solution of sulphuric acid. Over this is poured a solution of copper sulphate and a copper electrode is placed in this part of the cell. The solutions tend to stay separated because of a difference in their specific gravities. These cells are sometimes called gravity cells from this latter characteristic. When the cells are being used the zinc electrode tends to go into solution while the copper electrode increases in weight at the expense of the copper in the solution.

The dry cell is not actually dry but has its liquid chemicals partially held in sawdust or other absorbent material. The can holding these chemicals is made of zinc and is itself one of the electrodes. The electrode in the center is a carbon rod. The active chemical is ammonium chloride. To prevent gas bubbles from forming on the electrodes when the cell is in use, it is customary to put some manganese dioxide in the cell. Dry cells are in very common use in this country especially for portable radio sets. Very small dry cells are placed in groups in wax-covered boxes so that high potential differences are obtainable. This arrangement is in common use for "B" or plate current supply for stationary sets as well as portable ones. For this use we require high potentials,

but small currents, so that these very tiny batteries are able to supply the currents required from them. On the other hand, the large dry cells which are used to supply the filaments of the smaller radio tubes are required to supply considerable amounts of current. In testing these various kinds of batteries, it is therefore reasonable to test the large cells with a current measuring instrument (called an ammeter) and the "B" batteries with an instrument measuring potential difference (called a voltmeter).

New dry cells of the large type should show between 20 and 25 amperes when the ammeter is connected directly across the terminals, provided an ammeter with low resistance be used. The cell is probably usable until this test shows as low as five to eight amperes. Do not keep the ammeter on the battery for more than a few seconds, as the load which it draws is hard on the life of the battery. Test only one battery at a time.

"B" batteries are usable until the voltage reading falls to four-fifths of the value stamped on them. At about that time they introduce so-called battery noises in a receiver. These noises resemble the rumbling type of static. Do not attempt to test blocks of "B" batteries with an ammeter.

Electro Motive Force. We first discussed potential differences in the case of stationary charges. If we had connected two objects at different potentials by means of a conductor, charge would have flowed from one object to the other and both objects would have been reduced to the same potential.

But in the case of the two electrodes of a battery, if we attempt to bring the two electrodes to the same potential by permitting charges to pass from one to the other, we find that the chemical action of the cell replenishes the supply of charges at either electrode. The electrodes may then be thought of as a source of supply for maintaining a potential difference over conductors in an external circuit. We refer to this source of potential difference by the term *electro-motive force*. It is measured by the same practical units adopted for potential differences; namely, volts. We use the term *electro-motive force* for the potential difference

maintained at the expense of mechanical energy by a generator as well as for that supplied by batteries.

Storage Batteries. Storage (or chemically reversible) batteries are mostly of two kinds, "Edison" type and lead type. The standard Edison type has one electrode made of powdered iron and the other of an oxide of nickel. The electrolyte is a solution of potassium hydroxide. The Edison cell will stand a great deal of rough usage, is not seriously injured by letting the cells go dry, and is not harmed by completely discharging the cells. It has the disadvantage of not having a very constant electromotive force. The value of the e. m. f. falls off as the cells are used.

Lead storage batteries are made with both electrodes of compounds of lead and with an electrolyte of dilute sulphuric acid. When the battery is charged the positive electrode is lead dioxide (Pb O_2) commonly known as red lead, and the negative electrode is pure spongy lead. As the cell is discharged both electrodes through a series of chemical changes are converted into lead sulphate (Pb SO_4). These changes are reversible when energy is supplied to force electricity through the cell in the reverse direction.

Lead storage batteries have a greater e. m. f. per cell than Edisons. This e. m. f. falls off only slightly as the cells are used. In general then they seem to be more adaptable to radio uses than the Edison type; but they do have the disadvantage of requiring better care. It is necessary not to permit the electrodes to get dry. Evaporation of water from the electrolyte must be replaced with distilled water. Furthermore the cells must not be used when their charge is nearly exhausted. If they are so used the sulphation process goes so far that the lead sulphate tends to cake on the electrodes and does not remain porous, or spongy. Hence, when the battery is put on the charging current, the H ions and SO_4 ions in the solution are not able to attack the lead sulphate molecules of the electrodes easily, and so the chemical process involved in charging proceeds slowly if at all.

If the battery is not in too bad shape it can usually be brought back by charging it at about one-tenth of its rated charging

value for several days or a week. A battery which does not yield to such treatment can sometimes be "jolted" into action by charging at a very high rate, say two or three times its stated charging rate. When this method is resorted to, it is necessary to keep a thermometer in the electrolyte and to slow up or stop the charging when the temperature exceeds about 120° Fahrenheit or about 45° to 50° Centigrade.

Storage batteries are rated in terms of the amount of charge they can deliver; that is, in current times time. When a battery is called a ninety ampere hour battery it means that the battery will supply one ampere for ninety hours or two amperes for forty-five hours, etc. It does not mean, however, that the battery will supply ninety amperes for one hour. The standard type of battery should never be used to supply current at more than the rate that would discharge it in eight hours. That is, a ninety ampere hour battery should never be made to supply electricity at a greater rate than eleven amperes. This value is also the maximum rate at which the battery may be charged. You should always remember that this value based on an eight hour discharge is the outside limit. If you want your battery to have a long life, you will neither use nor charge your battery at much more than half this rated value. Large current flowing through a battery tends to heat and buckle the plates. Moreover hydrogen and oxygen gas tend to be formed at the electrodes, and if this does not all go into chemical combination it gathers in little bubbles of gas and breaks away from the electrodes. Little or no damage is done when this takes place to a moderate extent; but when it takes place violently and in large amounts, it tends to loosen the lead compounds packed into the electrodes, and this action combined with the buckling of the plates causes chunks of the lead compounds to fall out.

In the case of automobile batteries the effects above described are augmented by the shaking the battery gets as the machine travels. Moreover, automobile use requires very large currents, especially for starting. So that misuse of a battery in automobile duty seems unavoidable and the average life probably does not much exceed two years.

On the other hand, radio requirements from storage batteries are extremely reasonable, and with good care, a well-made battery

might be expected to stand up for many times the life of the automobile battery. I have seen batteries in physics laboratories stand up for over twenty years.

The habit of "trickle" charging now becoming popular is a very good thing. No harm is done the battery by over-charging if the rate of charge is very small as is the case with a trickle charger. Moreover, by this method the battery is never permitted to get near the stage of exhaustion.

There are certain features of slow charging currents and low rates of consumption which tend to offset to some extent the merits claimed above unless the batteries are especially designed for radio use. Automobile batteries are made with many but rather thin plates in each cell and the composition of the plates tends to be somewhat porous. This method of construction increases the ability of the battery to supply extremely large currents for short periods, as is necessary in starting an automobile. But when a battery is charged and used slowly, the chemical action involved in charging and using tends to penetrate more deeply into the plates than when high rates of charge and discharge occur. This constant chemical activity throughout the plate tends to loosen the active material and so increases its liability to fall out. If the batteries are to stand up for a great period of time, it follows from the above discussion that for low rates of charging and discharging the plates should be made thicker and contain slightly harder active material than would be used for automobile purposes.

Testing Storage Batteries. Lead storage batteries are commonly tested by examining the electrolyte with the aid of a hydrometer. This test is not of much value unless the hydrometer reading for that particular battery was known when the battery was first charged and in good condition.

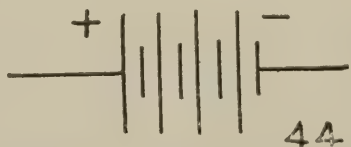


Fig. 44. Batteries in Series. *E. m. f.s are added*

Lead storage batteries develop an e. m. f. of from 2 to 2.1 volts or slightly more depending upon the strength of electrolyte used. However, if a test is made with a voltmeter, the battery should be made to supply current (at least as much as it supplies in ordinary use) while the potential drop is being measured with the

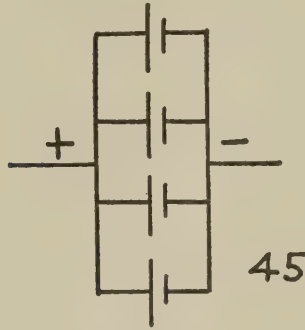


Fig. 45. Batteries in Parallel. E. m. f. is the same as that of a single cell, but larger currents may safely be drawn

voltmeter. If the battery is in poor condition it will show considerably less than two volts per cell when measured under these conditions.

Batteries are hooked together in series as shown by Figure 44 when it is desired to get the effect of their added e. m. f. s. Of course the current obtainable from such a combination is no greater than from one individual cell.

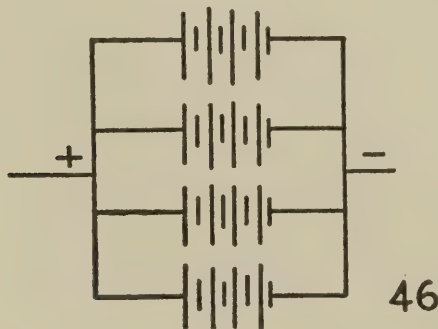


Fig. 46. Batteries in Series—Parallel. This arrangement is used to supply large currents and large e. m. f. s

When large currents are desired batteries are wired in parallel as shown in Figure 45. The current capacity of the cells are now added, but the e. m. f. is the same as that of a single cell.

When both large current and large potential are desired a series parallel arrangement such as is shown in Figure 46 is used. This combination has the e. m. f. of the number of cells in a horizontal row and the current capacity of the number of cells in a vertical column.

Storage batteries, as well as dry cells, are in common use both as "A" and "B" batteries.

Chapter II—Examples

1. Two condensers of values

$$C_1 = .02 \text{ mcf}$$

$$C_2 = .05 \text{ mcf}$$

are joined in series. What is the overall value of the capacity

$$\begin{aligned} C &= \frac{.02 \times .05}{.02 + .05} \\ &= \frac{.001}{.07} = .0143 \end{aligned}$$

2. Three condensers of values

$$C_1 = .1 \text{ mcf}$$

$$C_2 = .5 \text{ mcf}$$

$$C_3 = .2 \text{ mcf}$$

are joined in parallel. What is the overall capacity?

$$\begin{aligned} C &= .1 + .5 + .2 \\ &= .8 \end{aligned}$$

3. If a dry cell can give 20 ampere hours of current how long can you expect one to last when used for heating the filament of a WD12 tube which takes $\frac{1}{4}$ ampere at 1.1 volts.

$$\frac{20}{\frac{1}{4}} = 80 \text{ hours}$$

4. A set containing two tubes that each take $\frac{1}{4}$ ampere at 5 volts is to be operated from dry-cells. How many dry-cells are required and how must they be arranged so that not more than $\frac{1}{4}$ ampere will be taken from each cell?

Since a dry-cell has an e. m. f. of approximately 1.5 volts, it will require 4 cells in series. This will give 6 volts. Two such rows of cells must now be connected in parallel in order that we may supply $\frac{1}{2}$ ampere to the tubes without taking more than $\frac{1}{4}$ ampere from each row of batteries.

Chapter II—References

Metallic Conduction

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**FUNDAMENTAL ELECTRICAL
THEORY**

(Continued)

TOPICAL INDEX

CHAPTER III

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CHAPTER III

Fundamental Electrical Theory

(Continued)

Conductors and Insulators. We have already considered the modern explanation of how electricity is conducted through a metal, and we have seen that it is the negative electricity that moves instead of the positive when we are speaking of metallic conductors. In the early days of electricity it was arbitrarily decided that electricity should be thought of as flowing from the positive pole of a battery through an external circuit to the negative pole. All of our rules relating the direction of electric currents and accompanying magnetic fields are based on this convention. Actually we have negative electrons going from the negative to the positive electrode.

If our present explanation of conduction of electricity through metals is correct we may conclude that any substance which has a large number of free electrons will be a good conductor and any substance which has a small number of free electrons will be a poor conductor. If a substance has an extremely small number of free electrons or none at all we would call the substance an insulator instead of a conductor.

It is evident that we may talk either about how easily electricity gets through a conductor and call it the conductance, or we may talk of the difficulty with which electricity is forced through a conductor and call it the resistance of the conductor. George Ohm conducted a series of experiments in which he measured the amount of current that would get through a given conductor for a known applied electro-motive-force. He found that if he doubled the e. m. f. the current would double. Expressed another way, he found that the ratio of the e. m. f. to the current flowing was a

constant provided that he kept the conductor at the same temperature. We may write this relation thus:

$$C = \frac{I}{E}$$

or

$$R = \frac{E}{I}$$

Where E is the applied e. m. f., I the current, C the conductivity, and R the resistance. It is evident that

$$C = \frac{1}{R}$$

R is measured in ohms and an ohm is the resistance of a conductor that will let one ampere pass when the applied e. m. f. is one volt.

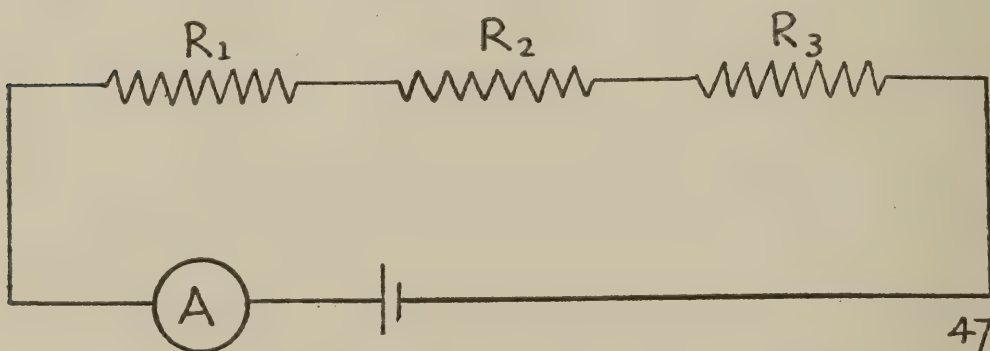


Fig. 47. Three Conductors Arranged in Series. The overall resistance is the sum of the individual resistances of the conductors

If conductors are arranged in series as in Figure 47 it is evident that the e. m. f. will have to overcome the resistance of all the conductors in order to force through any electricity. Hence, the resistance of the combination is given by

$$R = R_1 + R_2 + R_3$$

If the conductors are arranged in parallel it is evident that some of the electricity can get through one conductor while other charges can get through another. So that the conductance of the combination is the sum of the individual conductances. That is,

$$C = C_1 + C_2 + C_3$$

Or since $C = \frac{1}{R}$ we might write

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

For only two resistances in parallel this equation reduces to

$$R = \frac{R_1 R_2}{R_1 + R_2}$$

If R_1 is equal to R_2 then R has just half the value of either of the individual resistances. In any case the value of R is less than the value of the smallest resistance in the parallel combination. (The foregoing relations of resistance in series and parallel can also be proven by the use of the simple statement of Ohm's relation and some elementary algebra).

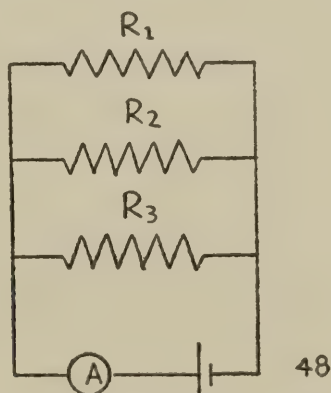


Fig. 48. Three Conductors Arranged in Parallel. The overall conductance is the sum of the individual conductances

The energy supplied by the source of e. m. f. applied to a conductor is used up in overcoming the resistance of the conductor.

Since work is involved in moving charges along a conductor, we may speak of the potential drop along a conductor. This potential drop over the entire conductor is of course equal to the applied e. m. f. We frequently then write Ohm's law as

$$R = \frac{\text{P. D.}}{I}$$

Later on we shall find that this law written in different form

$$\text{P. D.} = R I$$

will be useful to us in calculating potential drops along conductors.

Measurement of Resistance — High Resistance.

Before leaving the subject of conductors, it might be well to point out common methods for measuring their resistance. If the resistance has a very high value, 100,000 ohms or more, it can best be measured by applying a known e. m. f. to it and, by measuring the current that flows, the resistance can be calculated from Ohm's law. The current measuring instrument has to be a fairly good one—a milli- or micro-ammeter or even a galvanometer. If a galvanometer is used a single dry cell will provide a sufficiently large e. m. f. If a milli-ammeter is used it will be necessary to use from 10 to 100 volts of e. m. f. The resistance of the ammeter or galvanometer is so small in comparison to the resistance of the conductor being measured that the e. m. f. of the battery may be considered to be applied entirely across the resistance.

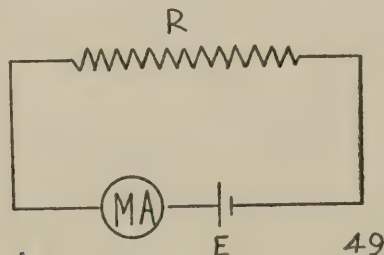


Fig. 49. The value of a high resistance can be determined with the aid of Ohm's law by observing the current which flows through the resistance upon the application of a known e. m. f.

Wheatstone Bridge. When resistances of more moderate value, say one ohm to fifty thousand ohms, are to be measured with some accuracy, another scheme is used. This arrangement, shown in Figure 50, is known as a Wheatstone bridge. It is well to consider its use here, for we shall see later that an extension of the



Fig. 50. A Wheatstone Bridge

electrical “bridge” to the case of alternating currents enables us to measure inductances and condensers, and also, we shall see that it has practical application in the construction of balanced tuned radio frequency receivers.

A very simple type of galvanometer will serve in this bridge for resistance measurements. The battery may be an ordinary dry-cell. R is a known resistance and X the unknown resistance

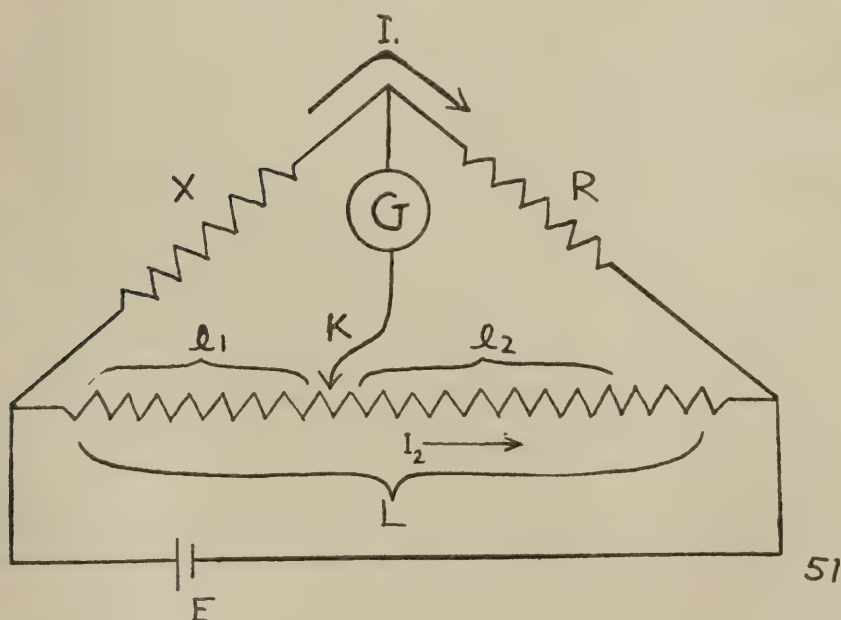


Fig. 51. Wiring Diagram of a Wheatstone Bridge for Measuring Resistance

to be measured. L is a piece of resistance wire stretched over a meter stick for convenience in measuring. The contact K is movable on this wire. Current from the battery flows through the circuit made up of R and X , and the potential drop over R will be $I_1 R$ and over X will be $I_1 X$.

If we call the length of wire to the left of K , l_1 , and that to the right of K , l_2 , we can say that the potential drop over this wire will be $l_1 I_2 R$ over the first section, and $l_2 I_2 R$ over the second section due to the current flowing from the battery through this wire. R is the resistance per unit length of this wire. In this discussion we have neglected any current that may be flowing through the galvanometer. Suppose that we move the contact K along the wire until the potential drop over X is equal to that over l_1 . This condition will be indicated by zero reading of the galvanometer showing that no potential difference exists across its terminals. Of course it follows that the potential drop over R is now equal to that over l_2 .

We may write these statements algebraically thus:

$$I_1 X = I_2 l_1 R$$

$$I_1 R = I_2 l_2 R$$

If we divide the first of these expressions by the second we obtain

$$\frac{I_1 X}{I_1 R} = \frac{I_2 l_1 R}{I_2 l_2 R}$$

which reduces to

$$X = R \frac{l_1}{l_2}$$

Best results are obtained when a value of R near the value of X is chosen so that the contact K comes somewhere near the middle of the wire.

A very compact form of this bridge containing a known resistance box for R and also the "ratio" wire, L , in the form of

small coils is made and sold under the name of a "post-office" box. The box form is a little easier to operate than the open form and it is more accurate for the measurement of resistances of less than an ohm.

The reader will find it profitable to build up an open form of Wheatstone bridge and acquire some technique in measuring resistances. He would also do well to measure some resistances in series and parallel and verify the laws already given. The only expensive item in the bridge is the resistance box.

We should note in passing that the value of resistance for a conductor changes when its temperature changes. The resistance of metallic conductors increases with increasing temperature. For changes of a few degrees the resistance change is small; but for large temperature changes the resistance change is of the utmost importance. For example, the resistance of a new gas filled mazda lamp filament when burning brightly is, for a one hundred watt lamp, about 120 ohms, whereas the resistance of the same lamp filament at room temperature is only about 10 ohms.

Insulators. We have already indicated that there is no sharp dividing line between conductors and insulators. In fact the insulating qualities of materials are sometimes specified in terms of their conductivity. Loss of electricity through an insulator because of its slight conductivity is known as "leakage."

Another property of insulators with which we are often concerned is their "disruptive strength." The application of high e. m. f.s seems able to free great numbers of electrons in some substances which under ordinary conditions show very small leakage. Even a piece of glass placed between two condenser plates can be punctured by a disruptive flow of electricity when the e. m. f. between the two plates is made sufficiently large.

One trouble that frequently occurs with insulators is leakage over the surface of the insulator due either to dirt or moisture on the surface.

Dielectrics. When an insulating material is placed between the plates of a condenser it is ordinarily referred to as a dielec-

tric. The most apparent effect of placing a dielectric between the plates of a condenser is to change the capacity of the condenser. That is, it will require a different quantity of electricity to bring the potential difference between the plates up to the same value with the dielectric present than is required without it. The dielectric value of a pure vacuum is taken as unity. The dielectric of any other substance can be found by comparing the capacity of a condenser when the dielectric is between the plates with its capacity when a vacuum, or for practical purposes, air is between its plates.

If the theory of atomic structure propounded early in this text be approximately correct, it is reasonable to suppose that when an atom finds itself in a strong electric field it might become somewhat distorted, with some of the electrons pulled off a bit to one side and the positive nucleus displaced to the opposite side of its central position. If this process does take place we would expect a loss of energy to take place upon charging a condenser with a dielectric between its plates. For the energy involved in "polarizing" the atoms of the dielectric would not be completely returnable upon discharging the condenser. The polarizing effect is not of great importance if the condenser is to be used for direct currents. But in almost all radio applications of condensers, alternating currents are applied across the condensers. The polarization loss occurs each time the condenser is charged and discharged; that is to say the loss occurs twice for every complete cycle of the alternating current. You can easily understand that if a condenser has appreciable polarization losses it could not be used on the part of a receiver where small currents of high frequency flow, for too large a percentage of the high frequency energy would be absorbed by the dielectric. Mica as a dielectric would be permissible on condensers in parts of the set where the frequencies of alternation are those in the audible range. High grades of waxed papers are sometimes used in audio parts of the circuit where the tubes and batteries supply so much energy that the loss to the condenser is negligible.

Energy and Power. We have already seen that the e. m. f. of a direct current source may be used up in overcoming the re-

sistance of conductors. The total amount of energy supplied depends on the amount of current that flows as well as upon the e. m. f. and it also depends on the time the current flows. Hence we write

$$P = E I$$

where P stands for Power or the rate at which we use energy, E is the electro-motive-force, and I the current.

Then

$$W = E I t$$

where W stands for the total amount of energy consumed in the time, t . If E is given in volts and I in amperes, P is given in watts. For commercial purposes t is given in hours and we pay our electric light bills in terms of watt hours or rather kilowatt-hours, since a watt-hour is a rather small unit of energy, and the kilowatt-hour is, as the name implies, one thousand times as large.

The equations just given do not hold at all accurately for alternating currents and for the power equation we write

$$P = E I \cos \theta$$

The term $\cos \theta$ is known as the "power factor." It occurs due to the fact that when alternating current is used on a circuit that contains inductance or capacity in addition to resistance, the maximum flow of current does not occur at the instant of maximum value of e. m. f. The value of this correction depends on the constants of the circuit and on the frequency of the current. It is not of great value to us here but will be given for reference.

$$\cos \theta = \frac{R}{\sqrt{R^2 + \left(2 \pi f L - \frac{1}{2 \pi f C} \right)^2}}$$

where f is the frequency and π has the value 3.1416. L is the inductance of the circuit and C the capacity.

It must be seen from the above discussion of energy and power that we do not buy electricity from the power company. What we really buy is energy transmitted to us through the medium of moving electrons. Consider especially the alternating current case. The electrons in a lamp filament hardly get a good start moving

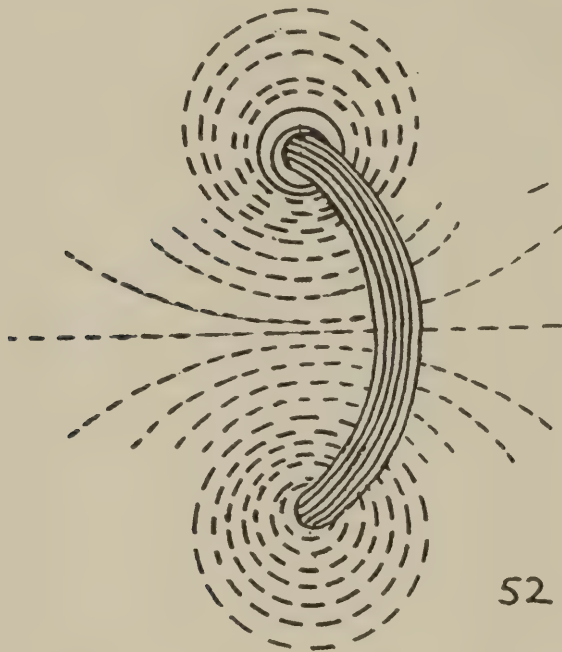


Fig. 52. Magnetic Field about Current Flowing in a Circular Path

in one direction until their motion is reversed and they drift the other way. This process is repeated 25 or 60 times per second, according to the frequency of our supply. The electrons thus vibrating speed up the vibrations of the atoms of the filament and we may say that the filament is heated and glows. The electrons that are being used to do the work were already in the tungsten filament when we bought the lamp. We merely hire the power company to shake these electrons to and fro.

Further Study of Magnetic Effects. We have already seen that when electricity is in motion a magnetic field whose direction is at right angles to the motion of the electricity exists. If the wire carrying the current is a long straight wire, the direction of the magnetic field is that of concentric circles about the

wire. (See Figure 39). If the wire is bent into a circular coil, the magnetic field is approximately as indicated by Figure 52.

Induction. We have also seen that when a conductor of electricity is moved across a magnetic field, a motion of electrons takes place in the conductor; and conversely, if a current is made to flow in a conductor lying across a magnetic field (that is, not parallel to the field) there will be a force exerted on the conductor. The first of these principles is applied in the operation of generators and the second in the operation of motors. The currents induced by the relative motion of conductors and magnetic fields we have called induced currents.

Let us now think of just one coil of wire without any magnets or other coils of wire carrying current. Suppose that we apply the electrodes of a battery to the terminals of this coil. When the current starts to flow we are, of course, establishing a magnetic field in the coil. But we have already seen that changing the magnetic flux enclosed by a conductor gives rise to e. m. f.s within the conductor that cause currents to flow in such a direction as to oppose the change of the magnetic flux. Evidently in this particular case, this induced e. m. f. will be opposed to the e. m. f. of the battery and tend to prevent the flow of current from the battery. This characteristic of a coil of wire, or in fact of any conductor, is known as *self-inductance*.

The value of the induced e. m. f. in each turn of the coil is equal to the rate of change of magnetic flux, that is, the change of flux per second. Of course the rate of change of flux is also proportional to the rate of change of current in the coil; so that we may say the induced e. m. f. is proportional to the change of current. We may write this mathematically thus:

$$E = -L \frac{di}{dt}$$

$\frac{di}{dt}$ is the rate of change of the current and E is the induced e. m. f. L is the proportionality factor that is necessary to convert the rate of change of current into the proper value for the e. m. f.

for the particular coil under consideration. L is called the inductance of the coil, or the coefficient of self-induction.

The unit of inductance is the henry. It is the inductance of a circuit in which one volt is induced when the current in the circuit changes at the rate of one ampere per second. Coils wrapped on iron cores may easily be made to have inductance as great as 50 henries or more. Small air core coils such as are used in tuned radio frequency circuits have values of the order of magnitude of .0002 henries (200 micro-henries).

If we increase the number of turns in a given coil the self-inductance increases as the square of the increase in the number of turns. That is, if we double the number of turns in a coil we multiply the self-inductance by four. This rule is not absolutely correct. If the turns of wire are all near together it is reasonably true, but if the turns are spread out as they are on a single layer straight solenoid type of core, the rule is only a rough approximation.

Simple Experiments with Induced Currents.

Some simple experiments might well be tried to check the foregoing discussion of induction and self-induction. The apparatus needed is simple as will be seen from this list:

- A simple galvanometer
- Two or three dry cells
- A bar magnet
- Two coils of wire.

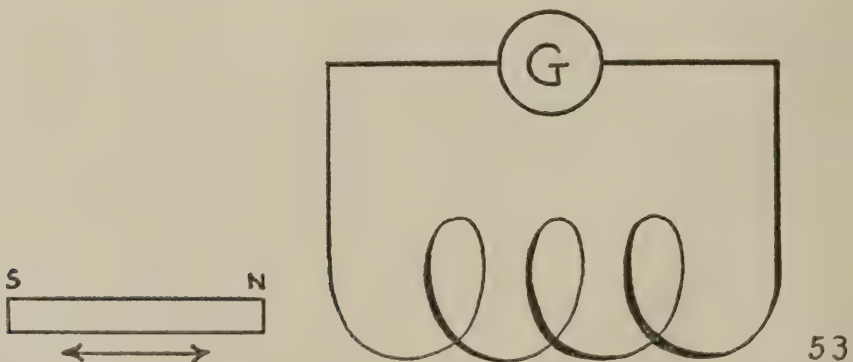


Fig. 53. When a magnet is moved either towards or away from a coil of wire, a galvanometer will show that a current is induced in the coil

First. We will connect both terminals of one coil to the galvanometer. Then if we thrust the magnet towards the coil or into it we should observe a deflection of the galvanometer. When the magnet is jerked away the galvanometer should deflect in the opposite direction. (See Figure 53.)

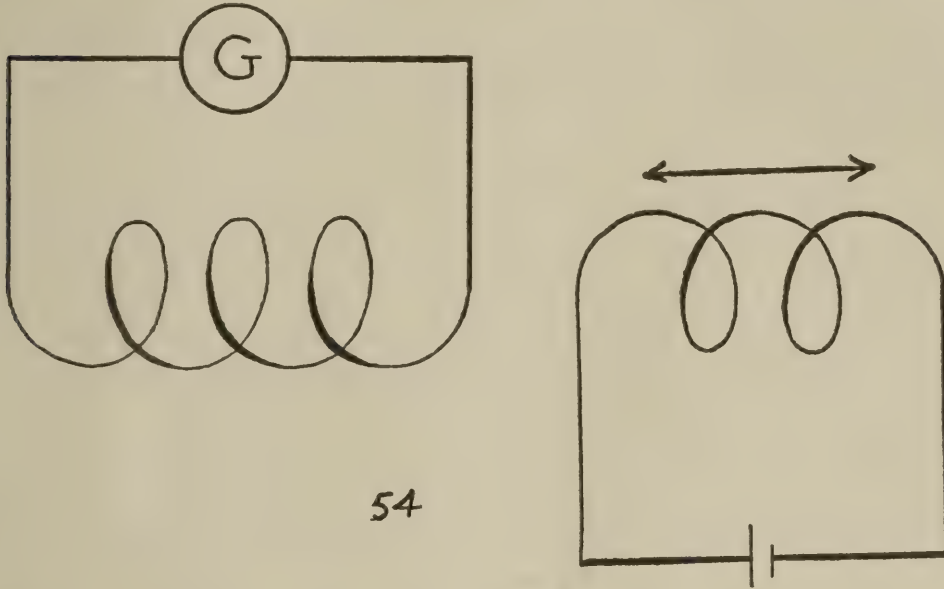


Fig. 54. When a coil carrying current is moved towards or away from another coil of wire, induced currents will again be observed

Second. We will now connect the other coil of wire to a dry cell (or two cells in series), and suddenly shove it near or into the first coil. (See Figure 54.) Again we should observe a deflection, and if the galvanometer is marked so that we can tell the direction of current through it we will see that the induced current flows in the opposite circular direction to the current in the coil connected to the battery. When this latter coil is jerked away the galvanometer will indicate a current opposite to the first induced current and hence in the direction of the current in the coil that is being removed.

Third. In this experiment we should place the coils near one another with the galvanometer attached to the first as in the other cases. (See Figure 55.) Instead of moving the second coil back and forth we will open and close the switch to the bat-

tery thus causing a starting and stopping of the current in the second coil. Again we will see that the galvanometer deflects and indicates a current opposed to the current on closing the switch and in the direction of the diminishing current in the second coil as the switch is opened. This experiment demonstrates the prin-

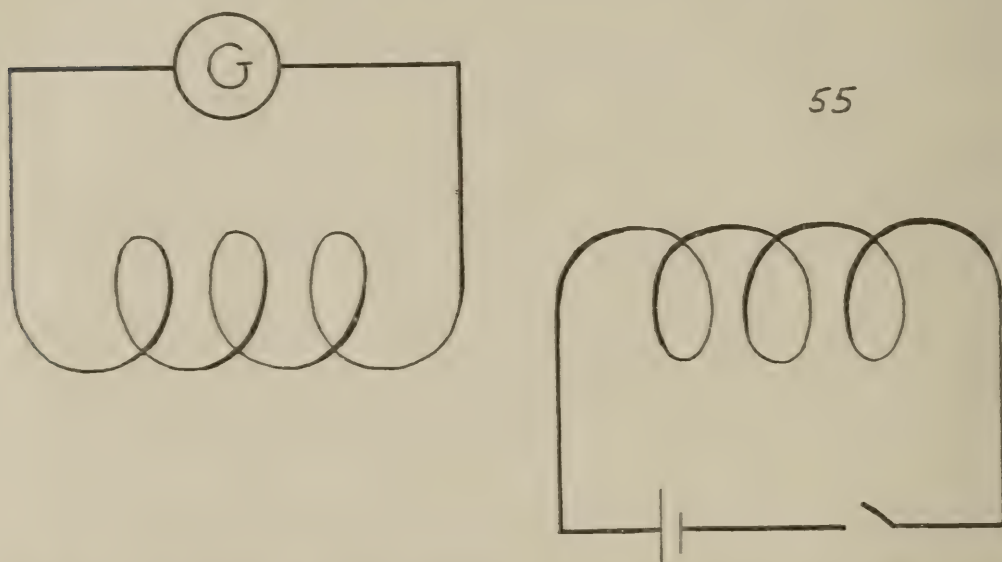


Fig. 55. When two coils are stationary, making and breaking the current in one will induce currents in the other

ciple of transformers, either power transformers with coils wrapped on iron cores, or "air core" transformers such as those used for radio frequency currents, or any other type. The inductive effect of one coil or circuit on another is called *mutual inductance*.

Suppose that we double the rate at which we make and break the circuit of the second coil. We will then double the number of pulses in the coil connected to the galvanometer. This line of reasoning leads us to the important conclusion that if we apply a source of alternating current to the second coil instead of a battery with a switch we should get alternating currents induced in the coil connected to the galvanometer. Coils so used are called transformers.

Power Transformers. The coil into which the supply of alternating current is fed is ordinarily called the primary and

the coil in which the induced currents flow, the secondary. If the average value of the e. m. f. across the terminals of the primary is E and the average value of the current flowing is I then the power going into the primary is given by EI as we have already seen. Some of this power is used up in overcoming the resistance of the wire in the primary. Hence the energy that can be transferred to the secondary must always be a little less than that put into the primary. If the two coils are closely coupled (i. e., so that their magnetic fields almost completely overlap one another) and if the amount of current permitted to flow through the secondary is not too large, then the average value of the voltage induced across the terminals of the secondary will bear the same relation to the value of E across the primary as the number of turns in the secondary bears to the number of turns in the primary. It follows from this fact that very high or very low voltages in comparison with those put across the primary may be obtained from the secondary. Of course the total power obtainable from the secondary will always be slightly less than that put into the primary. So if we increase the number of turns in the secondary and so obtain large e. m. f.s, we shall be able to draw only a correspondingly small current. If we try to draw a larger current than that given by the limiting condition

$$EI = E' I'$$

where E' and I' are the maximum average values of e. m. f. and current in the secondary, then the value of E' will fall off and be less than that predicted from the ratio of the number of turns in the secondary and primary.

We can also see that the resistance of the primary must be small as compared to the inductance if we do not wish to use up a lot of energy in overcoming resistance and heating the wire. This is another way of saying that if we expect to transfer large amounts of power it will be necessary to use a primary with wire of considerable size and to have it wrapped on a fairly large core.

From the discussion of the experiment described we may conclude that a given amount of energy can be transferred on each cycle of the alternating current. Suppose that we have two transformers and let us apply 60 cycle current to one and 25 to the

other. Since we are supplying energy 60 times per second in one case and 25 times in the other, it follows that if the two secondaries are to deliver the same amount of power, it will be necessary to put more energy across on each pulse with the 25 cycle than with the 60. Consequently it is necessary to use more turns in the primary and to wrap them on a larger core for the 25 cycle than for the 60 cycle. 25 cycle transformers are therefore larger and more expensive than 60 cycle transformers. In all transformers built for power transfer, iron (or soft steel) is used for the core. The energy is, of course, transferred through the medium of magnetizing and demagnetizing the core on each half cycle.

Transformers built to handle radio frequency currents usually have air cores. They do not in any sense approach the ideal conditions described above, and hence the value of E' across the secondary can not be predicted from E and the ratio of the turns in the two coils. We will discuss transformers for radio frequency currents later on.

Electron Theory of Self-Inductance. We might also think of self-induced currents from still another point of view. Every electron has its electric field extending out in all directions from itself. When the electron is moved its electric field must be moved with it. Now an electron with its electric field appears to have mass or inertia just as large pieces of matter do. If an automobile is standing on a perfectly level roadway, we must do a considerable amount of work to get it up to any speed, say 25 miles per hour. On the other hand, once it is started, we can remove the power and it will coast for a considerable distance before the frictional losses in the bearings and between the tires and road bring it to rest. In a somewhat similar way it requires the application of an electric field for an appreciable amount of time to get the electrons with their electric fields into any considerable motion. This is the self-induction effect when we apply a source of e. m. f. to the terminals of a coil. After the current is established, if we remove the battery and short circuit the ends of the coil through a galvanometer we observe that the current is continuing to flow in the same direction as that supplied by the battery. This effect corresponds to the

“coasting” of the automobile. The current is brought to a stop by the resistance of the wire to the flow of electrons.

Let us consider these effects as they would appear if we applied a source of alternating current to the terminals of the coil. Let us suppose that we close the switch to the alternating current

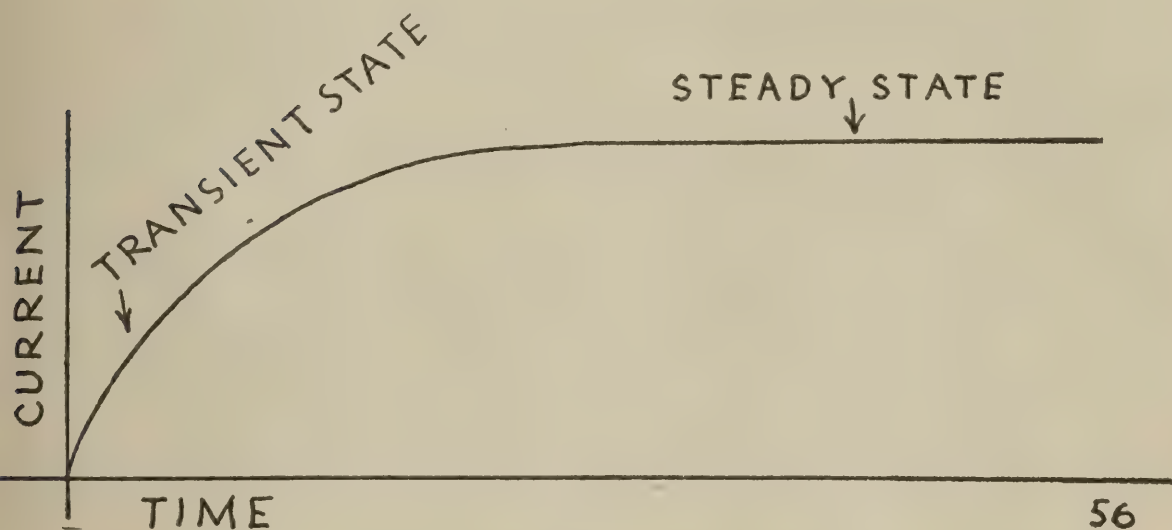


Fig. 56. Current through an Inductance when a Steady (Direct) E. M. F. is Applied

supply just as the alternating e. m. f. passes through zero value. Now the e. m. f. increases in one direction and attempts to overcome the inertia of the electrons. The e. m. f. arrives at its maximum value and begins to fall off, but still exerts some force on the electrons. The longer the force is applied the more the inertia of the electrons is overcome. Consequently we find the electrons moving fastest (i. e., the maximum current flowing), at a little interval after the applied e. m. f. has reached its maximum. Of course the current begins to grow smaller as the applied e. m. f. continues to get smaller, but some current will still be flowing in the original direction as the e. m. f. passes through zero. The e. m. f. then builds up in the opposite direction and the current also builds up in the new direction but as before the maximum value of current is reached after the maximum value of e. m. f. has passed. In engineering parlance, the current is said to *lag* behind the e. m. f.

in an inductive circuit. If the resistance of the coil of wire is great in comparison to the inductance, the lag is not great. But if the resistance is negligible in comparison to the inductance, the current may lag by nearly one fourth of a cycle. Figure 56 shows current plotted against time for the case of an inductance and a

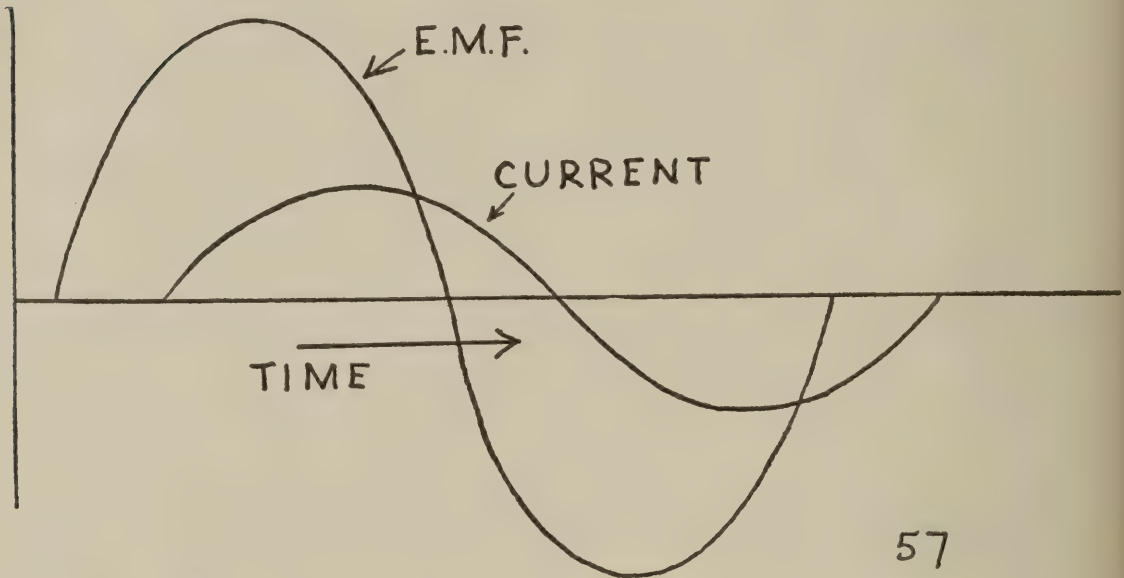


Fig. 57. In an inductive circuit the current lags behind the impressed e. m. f.

steady source of e.m.f. Figure 57 shows both an alternating e. m. f. and the current that flows through a given inductance. It is more or less evident that this inertia effect will become more noticeable as we increase the frequency of the applied e. m. f. If a coil be inserted in a circuit where both alternating and direct currents are flowing (that is, where there is a varying direct current), the coil will offer only resistance to the steady current but will offer both resistance and inductance to the fluctuating (or alternating) component. A coil used in such a way is known as a choke coil.

Chapter III—Problems

1. In a resistance coupled amplifier it is found that $\frac{1}{2}$ mil of current flows in the plate circuit. What part of the e. m. f. of the battery is used up in overcoming the potential drop across the 100,000 ohm plate circuit resistor?

$$\begin{aligned}\frac{1}{2} \text{ mil} &= .0005 \text{ amperes} \\ \text{P.D.} &= R \times I = 100,000 \times .0005 \\ &= 50 \text{ volts}\end{aligned}$$

2. How much power is consumed in the filaments of a set containing five 201-A tubes and one 112 tube?

The potential drop for all six tubes is 5 volts.
The current for each 201-A tube is $\frac{1}{4}$ ampere.
The current for a 112 tube is $\frac{1}{2}$ ampere.

$$\text{Power} = E \times I = 5 \left[(5 \times \frac{1}{4}) + \frac{1}{2} \right] = \frac{35}{4} = 8.75 \text{ Watts}$$

3. The primary of a transformer takes current from a 110 volt line. The primary contains 700 turns. The secondary supplies $\frac{1}{4}$ ampere at 550 volts. Find the number of turns in the secondary.

$$\frac{N_s}{N_p} = \frac{550}{110}$$

$$\therefore N_s = \frac{550}{110} \times 700 = 3,500 \text{ turns}$$

Find the current taken from the line. (Neglect all losses).

$$110 \times I = 550 \times \frac{1}{4}$$

$$\therefore I = \frac{550}{110} \times \frac{1}{4} = 1.25 \text{ amperes}$$

Chapter III—References

Resistance

A Text Book of Physics—DUNCAN AND STARLING,
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Electricity, Sound and Light—MILLIKAN AND MILLS,
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Any good text book of Physics

Dielectrics

Principles of Radio Communication—MORECROFT,
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Electricity and Magnetism—STARLING, pp. 301 ff.

**FUNDAMENTAL ELECTRICAL
THEORY**

(Continued)

TOPICAL INDEX

CHAPTER IV

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Impedance to Flow of Current

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Wave Trap

Size of Inductance

Size of Coils

Receiving Circuits

The Antenna

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Lightning Arresters

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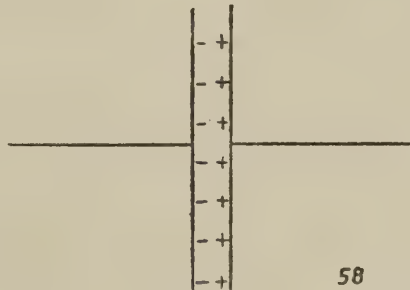
CHAPTER IV

Fundamental Electrical Theory

(Continued)

Applications to Radio Receiving

Condensers and Alternating Currents. In the second chapter we considered condensers from the point of view of static charges, and in the third chapter we considered polarization and absorption losses when condensers were to be used on an alternating current line. Let us now consider the relations between the applied e. m. f. and the current as we did in the case of inductances.

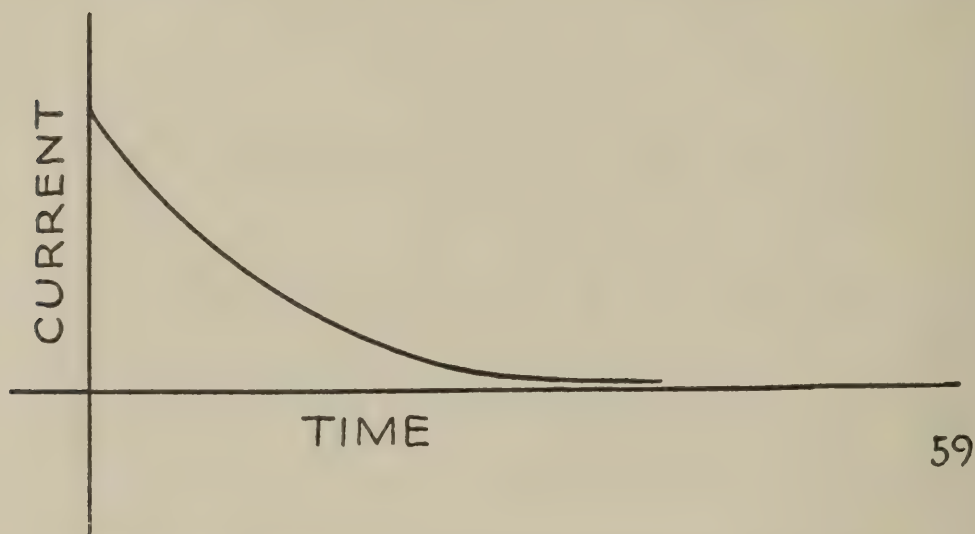


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Fig. 58. When an e. m. f. is applied across a condenser electrons flow into one side of the condenser and out of the other

Suppose that we close the switch to an alternating current source just as the value of the alternating e. m. f. passes through zero as we did in the inductance case. The condenser is at first uncharged and we therefore pass electrons from the line to the plates of one side of the condenser very easily even while the e. m. f. is still weak. These electrons repel electrons on the other plates and they pass into the line leaving the plates positively

charged. As the condenser acquires charge in this manner it becomes increasingly harder to put more electrons on the one plate and to take them away from the other. Consequently, although we are still getting a small flow of charge to the condenser as the e. m. f. passes through its maximum, yet the maximum flow of



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Fig. 59. Charging Current in a Condenser from a Direct Current Source

charge (i. e., current), took place at some time previous to the time of maximum e. m. f. As the e. m. f. dies away the charge flows out of the condenser, so that we actually have current flowing in the line in the opposite direction to the applied e. m. f. as the e. m. f. falls off and approaches zero and finally builds up again in the direction in which the current is already flowing. If we may again revert to the language of the engineer, we will say that in the case of a capacitative circuit, the current *leads* the voltage. Figure 59 shows the current plotted against time for the application of a steady e. m. f. to a condenser and Figure 60 the same quantities for the case of an alternating e. m. f.

It is apparent that while a condenser constitutes an open circuit for a direct current (except for the brief period of charging), it permits the passage of alternating current. The effect is dependent on the frequency of the alternating current, but whereas a high inductance hinders the flow of alternating current, a large

capacity facilitates the flow of the current. At high frequencies a small condenser will permit the passage of current quite easily.

Impedance to Flow of Current. There is one difficulty involved in attempting to calculate the impedance which inductances and capacities offer to the flow of current of given

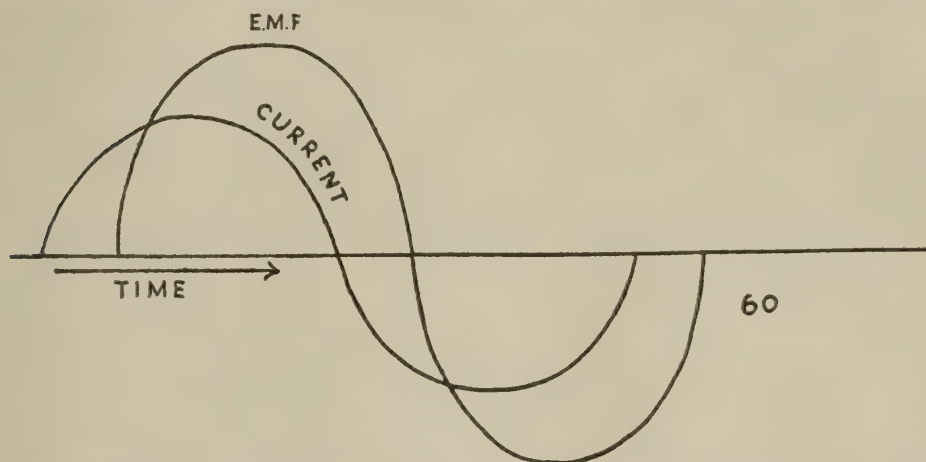


Fig. 60. When an alternating e. m. f. is applied across a condenser the current reaches its maximum value before the e. m. f. reaches its maximum

frequency. It is due to the fact that although maximum and minimum current coincide with maximum and minimum applied e. m. f. when there is only resistance in the circuit, they vary in the manner above discussed for inductances and capacities. The impedance of a pure inductance is given by

$$6.28 f L$$

where f is the frequency and L the inductance and the impedance of a pure capacity is

$$\frac{1}{6.28fC}$$

However, if these exist in a circuit with resistance, the combined "impedance" of the circuit is given by

$$\sqrt{R^2 + \left(6.28fL - \frac{1}{6.28fC} \right)^2}$$

This quantity is technically named impedance to distinguish it from pure resistance. The term in the parenthesis is called the reactance. We shall be concerned with this quantity just a little further on when we study tuned circuits.

Alternating Current Bridge. For the benefit of those who are experimentally inclined it might be well to digress here long enough to describe the most common method of measuring, or rather comparing, inductances and capacities. The scheme is known as that of an alternating current bridge and it bears some resemblance to the Wheatstone bridge used for measuring resistances with the aid of direct current.

In Figure 61 we have two arms of the bridge made of non-inductive variable resistance boxes, R_1 and R_2 . Two small resistance boxes r_1 and r_2 are usually used in the two inductive arms. The bridge is then first balanced as an ordinary Wheatstone bridge with a battery in the place of the alternating current source and a galvanometer in place of the telephone receivers. R_1 and R_2 are set to any arbitrarily chosen value and the values of r_1 and r_2 are then adjusted until the galvanometer shows no deflection. The known inductance L is a variometer; that is, two coils of

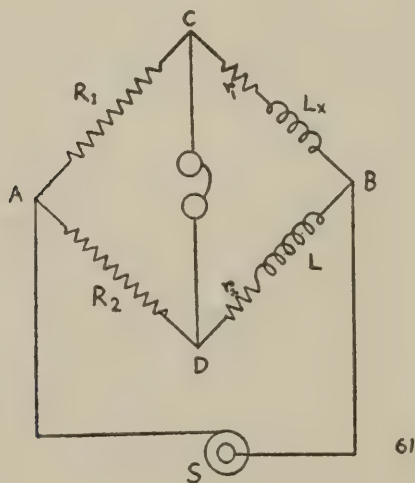


Fig. 61. An Alternating Current Bridge for the Comparison of Inductances

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EDWARD L. DOWLES

wire one of which may be turned so that the value of the inductance varies from

$$l_1 + l_2 - M \text{ for the smallest value to}$$

$$l_1 + l_2 + M \text{ for the largest value}$$

where l_1 and l_2 are the inductances of the individual coils and M is the mutual inductance.

We now apply an alternating e. m. f. at S and adjust the value of the inductance L until we get the minimum of sound in the telephone receivers. It can then be shown that the value of the unknown inductance will be given by:

$$L_X = L \frac{R_1}{R_2}$$

If we find no setting of L which gives nearly zero sound in the receivers, then the relative values of R_1 and R_2 must be changed and r_1 and r_2 must also be readjusted with the aid of the battery and galvanometer as in the first case.

It is evident that when we hear no sound in the telephone receivers, there is no difference of potential between the points C and D and the alternating potentials through the line ACB and ADB are in phase at C and D when an alternating e.m.f. is applied between the points A and B . This point will be worth our remem-

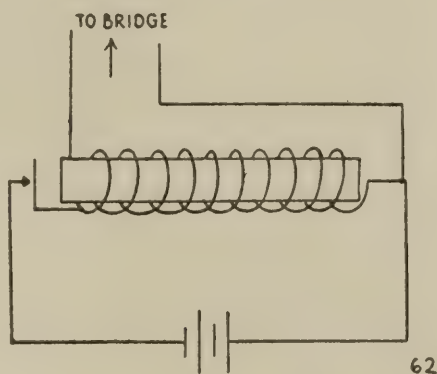


Fig. 62. An Ordinary Buzzer Arranged to Supply Varying e. m. f.s to an Impedance Bridge

bering when we come to the balancing or "neutralizing" of tuned radio frequency receivers.

The source of supply of alternating current in most laboratories is a "microphone hummer" which supplies alternating current at a frequency of 1,000. This frequency of current produces in the receivers a shrill tone to which the ear responds very well. In the absence of such a source, a buzzer may be used with fair results. It may be connected as shown in Figure 62 or the buzzer may be wound with one or two hundred turns of wire as a secondary and this secondary used as the source of e. m. f.

Capacity Measurement. Exactly the same form of bridge may be used for the measurement of capacity. In this case, if accurate results are desired one should procure a good standard variable condenser for C . He will then arrange the apparatus following the diagram of Figure 63. It is quite evident that no direct current balance can be obtained by the use of the galvanometer and battery, for the condensers are an open circuit for direct currents. One should, therefore, first set r_1 and r_2 at zero and adjust C and the ratio resistances R_1 and R_2 until a minimum of sound occurs. Then increase either r_1 or r_2 to reduce the sound still further and readjust R_1 , R_2 , or

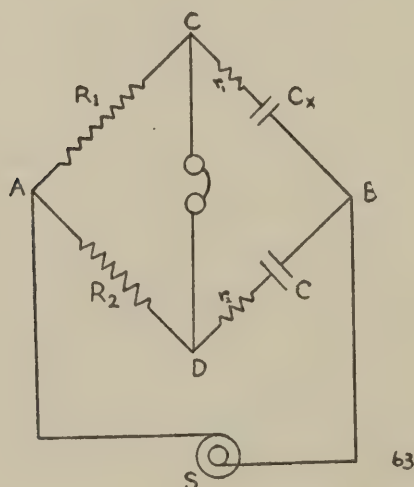


Fig. 63. An Alternating Current Bridge for the Comparison of Capacities

C. Continue this process until the condition of least possible sound is heard in the telephone receivers. The value of C_x is now given by:

$$C_x = C \frac{R_2}{R_1}$$

Simple Form of A. C. Bridge. Fair results can be obtained with somewhat more simple apparatus. r_1 and r_2 may be omitted entirely. The wire of an ordinary Wheatstone bridge may be substituted for R_1 and R_2 and the point A will be the variable contact on the wire. The ratio of the two lengths of the wire will then be substituted for R_1 and R_2 . So that we will have

$$L_x = L \frac{l_1}{l_2}$$

and

$$C_x = C \frac{l_2}{l_1}$$

The bridge will give better results if one side of the alternating current supply is connected to a good ground.

Phase Angle of a Condenser. We hear much of late about the "phase-angle" of condensers. We have already seen that when an alternating electro-motive-force is applied to a perfect condenser, the maximum value of current occurs one-fourth of a cycle ahead of the maximum value of electro-motive-force. If, however, the groups of condenser plates are not well insulated from one another, so that leakage takes place, or if there is an absorption of energy by dielectric material either between the plates or in their vicinity, then the current does not lead the e. m. f. by a full quarter cycle, but by a little less than this value. For analytical purposes a full cycle of alternating current is referred to in angular units and called 360° . If it happens that the current leads the e. m. f. across a given condenser by only 89° we speak of a phase angle of 89° or a "phase difference" of 1° . For a further discussion of phase difference and methods of measurement the reader is referred to an excellent treatise on

Electrical Measurements, by Frank A. Laws, especially Chapter VII on Measurement of Inductance and Capacity. It may be well to point out that any reasonably well-made condenser has losses that are small in comparison with the losses of the coils to which the condensers are attached. So it is hardly worth being too exacting about small losses in the condensers. The almost general discarding of dielectric end plates in favor of metal ones during the last few years is justified not so much by electrical improvement as by the demands of the public who have heard the magic words "Low Loss" and who will buy only the newer, but frequently not better, condensers with metal end-plates.

Tuned Circuits. In Figure 64 we have a circuit containing inductance, resistance and capacity. Suppose that the battery shown in the figure has been connected for some time so that the condenser will be charged to the point where the potential difference between its plates is equal to the e. m. f. of the battery. Let the battery be removed and the circuit closed. The negative charge on one side of the condenser will flow out into the rest of the circuit and tend to neutralize the positive charge on the other side of the condenser.

In this manner a current will be set up through the inductance, and in the manner already described in Chapter III this current will continue to flow even after the condenser is discharged, so that the condenser is forced to become partly charged again but in the opposite direction to that resulting from the battery. This process then repeats until the current finally dies away as the energy is dissipated in overcoming the resistance of the circuit. Figure 65 shows a picture of the discharge current in this circuit. What

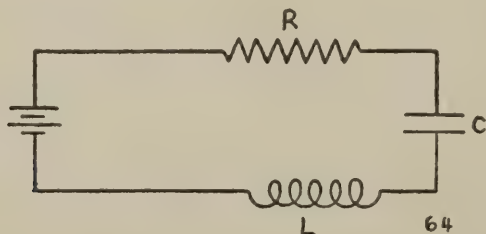


Fig. 64. A Circuit Containing Resistance, Inductance, and Capacity in Series

interests us here is not only the fact that we get an oscillatory discharge, but also the fact that the frequency of these oscillations can be predicted from the constants of the circuit. A mathematical treatment of the circuit leads us to the following expression for the frequency

$$f = \frac{1}{2\pi\sqrt{LC}} = \frac{.1592}{\sqrt{LC}}$$

where L is expressed in henries and C in farads (not micro-farads) and experiment checks the formula as being correct. The formula is valid only when the resistance of the circuit is small.

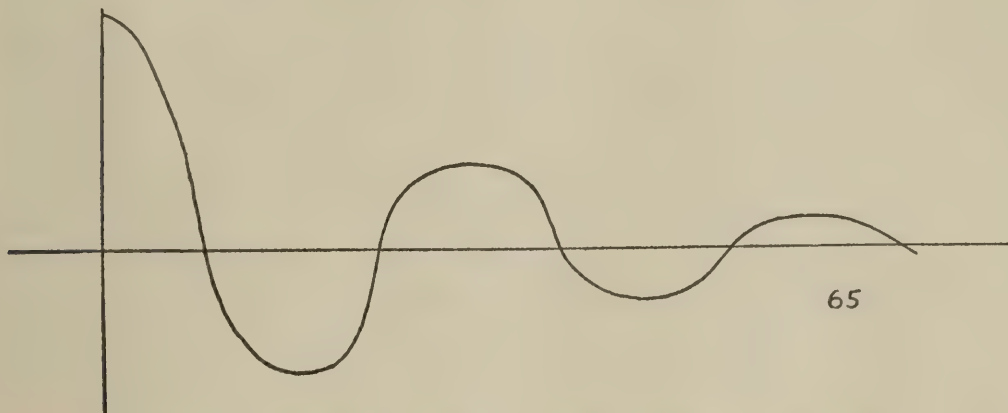


Fig. 65. Discharge Current in a Circuit Containing Resistance Inductance and Capacity

Consider now the circuit of Figure 66 where a source of alternating current has replaced the battery in the preceding circuit. If we observe the ammeter while we vary the frequency of the source of alternating current without varying the e. m. f., we will

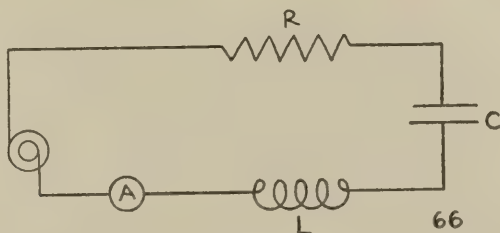


Fig. 66. The amount of alternating current flowing in a circuit containing inductance and capacity depends partly on the frequency of alternation

notice that the maximum current flows when the applied frequency is the same as that of the natural frequency of oscillations of the circuit as discussed above. We now say that the circuit is "tuned" to this particular frequency or that it is *resonant* to the frequency

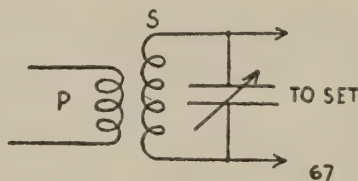


Fig. 67. The Input Circuit of a Radio Set

of the source of alternating current. If we again refer to the results of mathematical treatment we find for this frequency that

$$6.28fL = \frac{1}{6.28fC}$$

This, of course, states that the reactance of the circuit to this frequency is zero so that it behaves as though resistance only were present. We can, of course, say as before,

$$f = \frac{.1592}{\sqrt{LC}}$$

The principle just discussed is the one applied in the most common form of tuning in radio sets. Energy is fed into the tuned circuit by means of magnetic coupling with the primary coil as

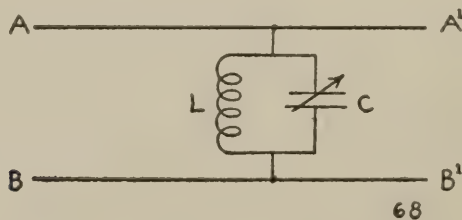


Fig. 68. A "Filter" Circuit to eliminate all Frequencies but One

shown in Figure 67. This primary may carry currents of ten or twenty or more frequencies, but for every frequency except one, there will be reactance as well as resistance in the tuned circuit. Consequently this tuned circuit will carry a far greater current at the resonant frequency than at any other. This is the fundamental scheme employed to gain selectivity in a radio receiving set.

Suppose that we have a tuned circuit employed as shown in Figure 68. The wires A and B may lead to a source of many different frequencies of e. m. f. If the coil L be of low resistance, we will find that all frequencies will be short circuited between the lines A and B by this coil except the frequency which gives resonance for the coil condenser combination. Current of this frequency will flow in the tuned circuit according to the theory we have just studied for series resonance, but the circuit will not absorb much energy from the line. In fact the tuned coil-condenser combination will act as a high resistance between the two lines instead of as a short circuit, so that only this frequency will be passed on to the apparatus connected to A' and B'. This type of resonance is known as parallel resonance. It is used in radio

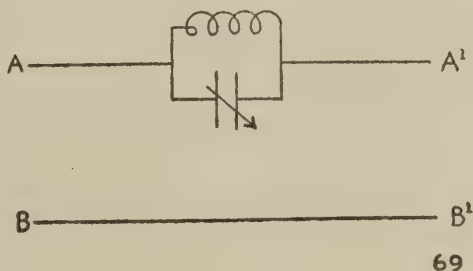


Fig. 69. A Filter Circuit to Pass all Frequencies but One

receivers employing what is called tuned impedance. We shall discuss this application later.

A more obvious case of parallel resonance is shown in the circuit of Figure 69. Here all frequencies are passed on except the one for which the coil condenser is tuned. This coil-condenser arrangement may be inserted in an antenna lead to serve as a wave trap. If the combination be tuned to the frequency

of some nearby transmitter it will act as a large resistance for that frequency but permit others to pass.

Wave Trap. A more common form of wave trap, however, is that shown in Figure 70. Here L_1 consists of only three or four turns wrapped directly on top of L_2 which consists of about fifty turns of wire wrapped on a three inch form. C is an ordinary variable condenser of about .0005 micro-farads capacity. When the

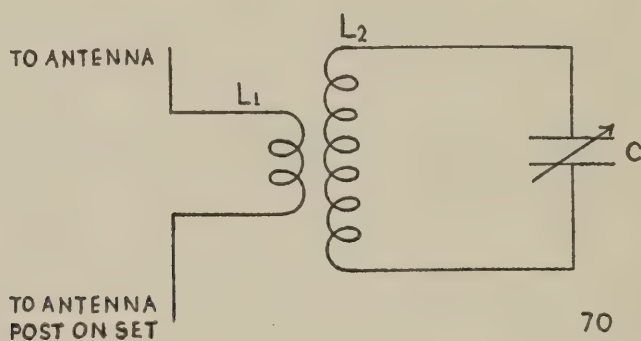


Fig. 70. A "Wave-Trap" to Eliminate Powerful Local Signals

condenser is adjusted to tune the combination for the frequency of the station to be eliminated, nearly all of the energy in the antenna circuit on this frequency is absorbed by this resonant circuit and very little passes on to the set. Wave traps are not usually necessary since multi-stage radio frequency sets with shielded coils and super-heterodynes have come into more general use, unless, of course, one is so unfortunate as to be extremely close to a powerful transmitter.

Size of Inductance. The calculation of the sizes of inductances to go with condensers of given size is a simple matter. Suppose that one wishes to build a radio receiver to use in the broadcast range and wishes it to tune from 200 to 550 meters in wave length. By reference to our previous discussion of wave-lengths and frequency we see that these wave-lengths cor-

respond to frequencies of 1,500,000 and 545,454. If now we wish to use a .0005 micro-farad condenser we take our equation for resonance and fill in as follows

$$f = \frac{1}{6.28\sqrt{LC}}$$

$$\begin{aligned}\therefore L &= \frac{1}{39.5f^2C} = \frac{1}{39.5 \times (545,454)^2 \times .0005 \times 10^{-6}} \\ &= .00017 \text{ henries}\end{aligned}$$

If we had wished to use a condenser whose maximum value is .00035 we would have found that

$$L = \frac{1}{39.5 \times (545,454)^2 \times .00035 \times 10^{-6}} = .000243 \text{ h.}$$

Size of Coils. It is now of interest to determine the size of coils in terms of their dimensions and number of turns that will give inductances of these values. We shall use a well-known formula that has been worked out for this purpose.

$$N = \frac{L \times 25,300,000}{r^2 nK}$$

Where N = total number of turns

r = radius of coil in centimeters

n = number of turns of wire per centimeter

L = the inductance in henries

K is a number whose value depends on the length of the coil in comparison to its diameter. If the coil is about the length of its diameter $K = .7$ approximately.

For example let us use a 3 inch coil. The diameter in centimeters will be $3 \times 2.54 = 7.6$ cm.

$$\text{Hence } r = 3.8$$

If we let $n = 8$ then

$$N = \frac{.00017 \times 25,300,000}{(3.8)^2 \times 8 \times .7}$$

$$= 53 \text{ turns}$$

for the coil to use with the .0005 condenser. For the other condenser we would require a coil with more turns, as follows:

$$N = \frac{.000243 \times 25,300,000}{(3.8)^2 \times 8 \times .7}$$

$$= 76 \text{ turns.}$$

In actual practice these calculations are used to determine the approximate size of the coil, and then either the inductance of the coil is measured on a bridge or it is put into an actual set and the number of turns increased or decreased until the inductance has the right value or until a long wave length station, when tuned in, requires practically a maximum setting of the condenser.

Usually the calculated number of turns of wire is too great due to the presence of "distributed" capacity. When current is flowing through a coil, any turn of wire is at a slightly different potential than its neighboring turns. Adjacent turns of wire in a coil therefore act as tiny condensers. When we come to a study of tuned radio frequency receivers, we shall go into this subject of distributed capacity and its effects on the circuit.

Receiving Circuits. In the first chapter we considered in a general way the nature of the energy sent out by a broadcasting station, and the fact that this energy in the form of electro-magnetic waves causes alternating currents to flow in a receiving antenna or loop. These currents follow in frequency and relative

magnitude the large currents supplied to the broadcasting antenna by the transmitting apparatus.

The Antenna. A receiving antenna is ordinarily a single wire running horizontally and placed to be as free as possible from other wires or metal of any form. Preferably it should run straight. For maximum signal in the broadcast range a horizontal length of about one hundred feet at a height of say fifty feet should be used. Actually the height is usually determined by the facilities available. A short antenna gives reduced signal strength but greater selectivity and probably slightly less disturbing noises such as static. An antenna of sixty feet will give some reduction in signal strength, but will increase the selectivity considerably. Very short antennas, fifteen to twenty-five feet, are often used with multi-stage radio frequency receivers, where the amplification in the set compensates for the weakness of the signal in the antenna.

It makes very little difference whether an antenna is outdoors or in the house provided it is equally free from grounded metal or large enough metal pieces to affect the capacity of the antenna. The wood or brick of a house has no measurable effect on the signal strength, but ordinarily it is not possible to keep as far away from wires in a house as out-of-doors. A metal roof acts as a shield and makes an antenna placed close to it nearly worthless. If the house has metal eave troughs or a metal ridge pole, an antenna should be kept several feet away. Many people think that if they use sixty feet or more of wire in the horizontal part of the antenna that it makes no difference how it is placed. So we find people who own houses with small square attics running the wire around in the attic instead of getting a straight stretch of sixty feet. Of course such a device works after a fashion. Bed-springs and various other convenient pieces of metal covering appreciable space are often used with varying degrees of success. But if we are interested in the very best of absolutely dependable results we must discard the freakish no matter how well it sometimes works, and insist on a good standard type of antenna.

Grounds. Where it is possible to do so the antenna should be so placed as to make the lead-in to the set as short as possible.

It is also desirable to have the lead wire to the ground short. Just as in the case of an antenna, any large piece of metal will serve as a ground; but best results are obtained when a good ground is used. A cold water line is usually the best ground obtainable. Hot water lines and heating systems, if connected to the cold water line at some point, will serve in a fairly satisfactory manner.

Lightning Arresters. In passing, it may be well to mention the use of lightning arresters. Insurance regulations require that a lightning arrester be placed as close as possible to the point where an outdoor antenna enters a building. Actually there is no great danger of fire from lightning striking an antenna. People who live in private houses instead of apartments frequently use (for hanging out clothes) wire lines having an end attached to the house. An ungrounded metal ridge pole on the roof of a house is essentially a well-insulated antenna. An ungrounded eave trough is the same sort of thing. We have used these things for generations, but when we attach a radio receiving set to one end of the wire or metal we are suddenly told that we have a fire menace. Actually, if the antenna is grounded, it will serve as a slight protection against lightning in the same manner that lightning rods often seen on farm houses serve, although the protection derived from the antenna will be negligibly small. Lightning arresters, however, do serve one useful purpose, and that is to permit static charges to leak off the antenna. Occasionally during rain and frequently during snow storms, an antenna becomes charged with electricity from the drops or flakes which touch it and which were previously charged. This charge often becomes large enough to cause sparks to jump between the plates of an antenna tuning condenser. Of course, if the antenna goes to a coil the other end of which runs directly to the ground, as is common in most modern sets, these charges never accumulate, but flow constantly and directly to the ground. Hence it would seem that a lightning arrester will have to be included in a radio receiving equipment, not primarily because of its usefulness but because the insurance companies require it. No arrester is required with an indoor antenna.

Crystal Detectors. We saw in the first chapter that the first essential to getting audible sound from the high frequency currents flowing in the antenna was rectification so that we could get pulses of current flowing in one direction only. The best of the more simple forms of detectors is the crystal. In the earlier detectors a small piece of galena, or silicon was clamped in a solid holder and a contact was made to the silicon by means of a small movable wire called a "cat-whisker" because of its appearance. The natural crystals were sensitive in only a few places on the surface and consequently much time was spent by the early operators in keeping the cat-whisker on a good place on the crystal. Many synthetic crystals have now appeared and are sold with a short piece of wire already located on a good spot on the crystal, or else are sufficiently sensitive over their entire surface to make adjustment a simple process. Some crystal detectors have appeared in which contact is made between two crystals of different kinds. Some of these seem to be superior to the older single crystal type. A very enlightening discussion of the characteristics of various types of crystal detectors may be found in the reference to Morecroft cited at the end of this chapter.

Crystal detectors are now used primarily for only two purposes: first, for use in a head-phone receiver to be used on strictly local stations, and second, for use as the detector in some types of reflexed sets. In the first chapter we considered some circuits of this first type and later in this series we shall consider the second use of crystal detectors. It would pay the reader to review the simple circuits for crystal receiving sets given in the first chapter, for these basic circuits are in common use in tube sets.

Chapter IV—References

Measurement of Inductance and Capacity

Electrical Measurements—Laws—Chap. VII.

Crystal Detectors

*Principles of Radio Communication—MORECROFT—
pp. 343-350*

Formula for Inductance

Bureau of Standards Circular No. 74—pp. 250-286

The more serious students will find a very enlightening treatise on fundamental electrical concepts especially as applied to the flow of alternating currents in reactive circuits in

*Principles of Radio Communication—MORECROFT,
Chap. I, II, and IV*

THREE ELECTRODE TUBES AND
THEIR USES IN SIMPLE
CIRCUITS

TOPICAL INDEX

CHAPTER V

Three Electrode Tubes and Their Uses
in Simple Circuits

Characteristic Curves

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CHAPTER V

Three Electrode Tubes and Their Uses in Simple Circuits

BEFORE going far into the construction of receivers employing three-electrode tubes it will be necessary to make a much further study of the characteristics of tubes than we have so far done. If the reader chooses to go over this discussion of tubes hastily in order to get to the more distinctly radio set discussions, he may do so provided that he later returns to a study of this section. The tubes are the heart of any radio receiver: one can not know too much about them and their behavior.

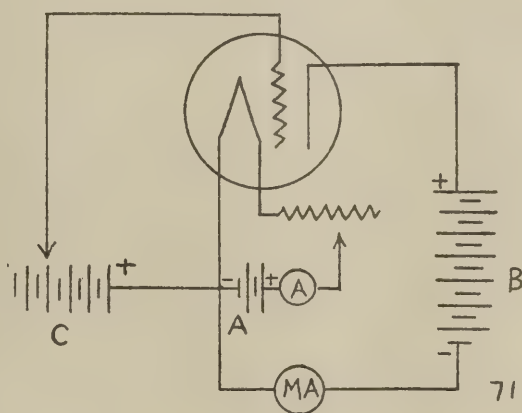


Fig. 71. Circuit for Determining "Static" Characteristic Curves of a Three-Electrode Tube.

Characteristic Curves. Every reader who has a voltmeter and a fair milliammeter at his disposal should actually make the measurements here suggested for three or four or more of the tubes now on the market. In Figure 71 we

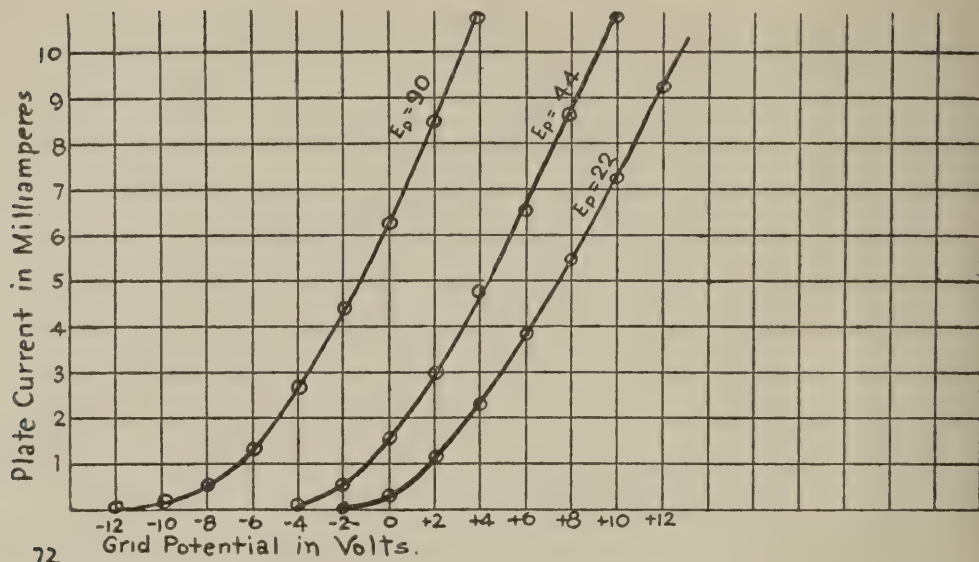


Fig. 72. Grid potential-plate current curves for a UV 201-A tube. Notice that the same value of plate current may be obtained for different values of plate potential (E_p) if the grid potential is changed to the correct amount

see the arrangement for determining the Grid Potential-Plate Current curve. The voltmeter (not shown in the diagram) is used to measure the potentials of the batteries. If the C battery be made of individual large dry cells, sufficiently accurate results will be obtained by considering each cell to have

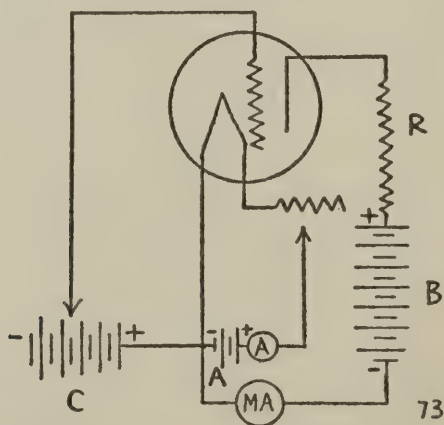


Fig. 73. Circuit for Characteristic Curves of a Tube when There Is a Load in the Plate Circuit

an e. m. f. of 1.5 volts. First operate the tube with its rated value of filament current. (If an ammeter for use in the filament circuit is not available, use the value of e. m. f. across the filament terminals that is specified on the tube carton). Apply any value of plate potential desired. Then vary the contact of the grid to C

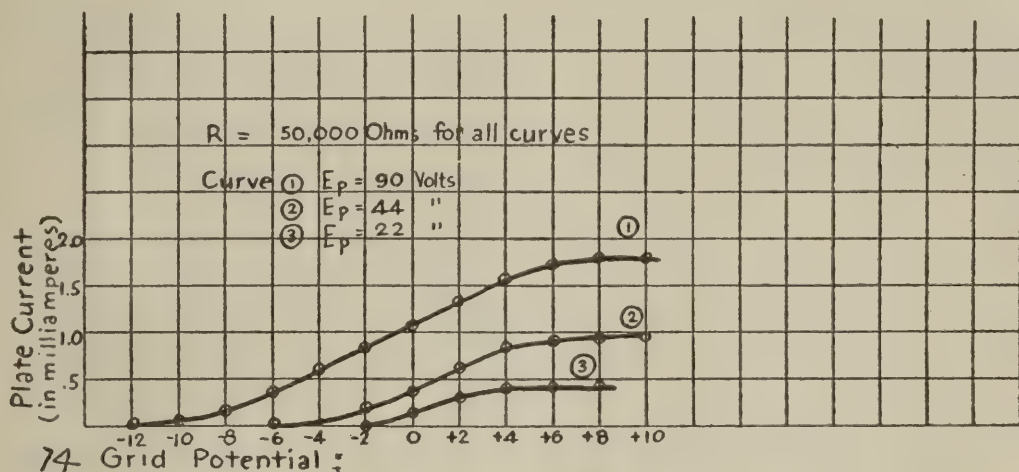


Fig. 74. Grid potential-plate current curves for a UV 201-A tube when there is a load in the plate circuit

battery and observe the changes in the plate current as indicated by the milliammeter. Figure 72 shows a great many such curves for a UV 201-A tube, each curve for a different value of the plate battery as indicated. This experiment should now be repeated with a 50,000 ohm resistor in the plate circuit as shown in Figure 73. Figure 74 shows a group of these curves. Figure 75 shows several curves for the same value of plate potential, one without the resistor and the others for various values of resistance as marked on the figure.

Amplification Factor. From the curves without resistance in the plate circuit we may obtain the theoretical amplification factor of the tube. We note from Figure 72 that the same current is flowing in the plate circuit for Grid Voltage (E_g)—4.8, and Plate Voltage (E_p) +90 as for E_g +.8, E_p +44. That is, a

change of 5.6 volts in E_g is equivalent to a change of 46 volts in E_p . Hence we say that the amplification factor is

$$\frac{46}{5.6} = 8.2.$$

This amplification factor (μ_o) is the one always given by tube manufacturers. In actual use current changes in the plate circuit resulting from voltage changes in the grid circuit are only available when they can be used to produce voltage changes across resistances or inductances in the plate circuit.

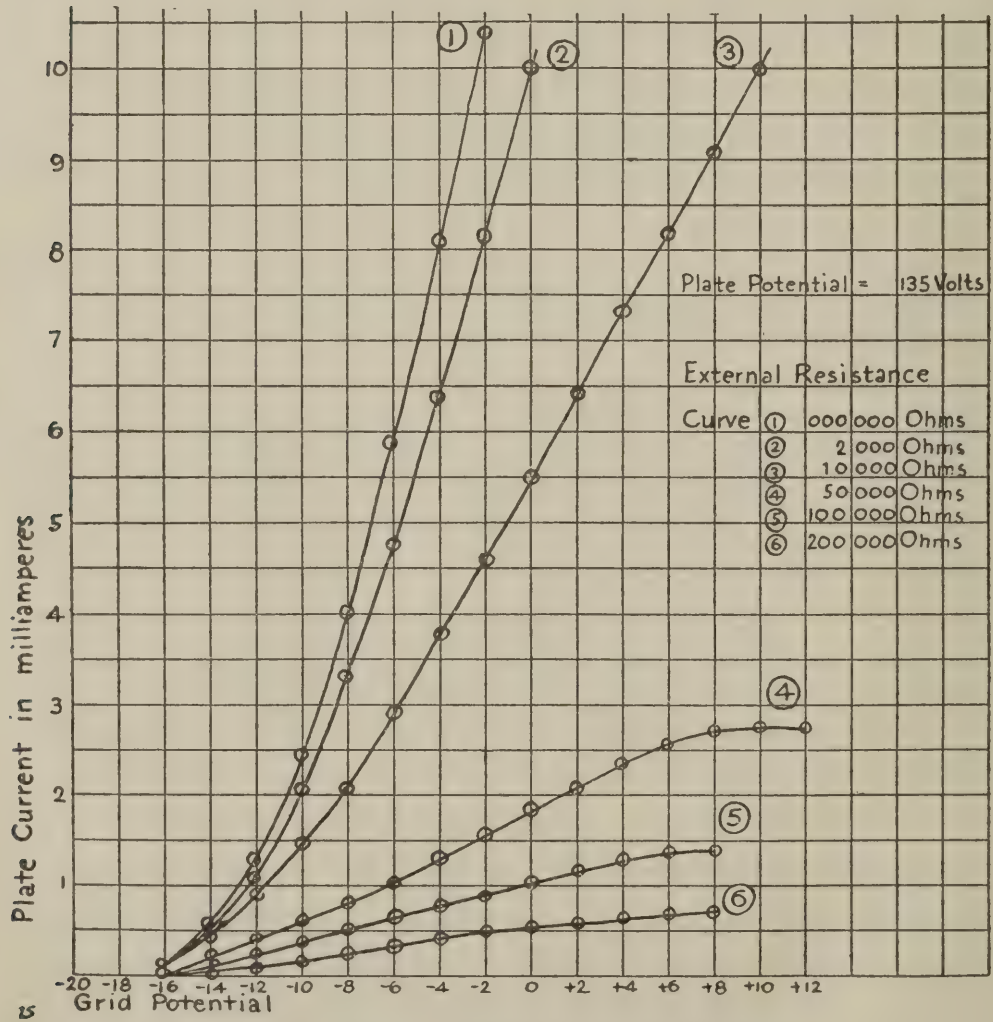


Fig. 75. Effects of Resistance in the Plate Circuit

Available Amplification. Suppose then that we note the curves with the resistor in the plate circuit. When the plate current changes, the potential drop across the resistor will change according to Ohm's law

$$dE = RdI$$

where we write dE for the change in potential across R and dI for the change in current through the resistor. If a change in grid potential of dE_g produces the change dI then the available amplification will be given by the ratio of dE to dE_g .

$$\mu = \frac{dE}{dE_g} = R \frac{dI}{dE_g}$$

This available amplification factor μ will always be less than the theoretical value μ_o .

We might take the curve for plate potential 90 from Figure 74. We note here that when the change in plate current (dI) is .00095 amperes the corresponding change in grid voltage (dE_g) is 8 volts. Hence we have

$$\mu = R \frac{dI}{dE_g} = 50,000 \frac{.00095}{8} = 5.9$$

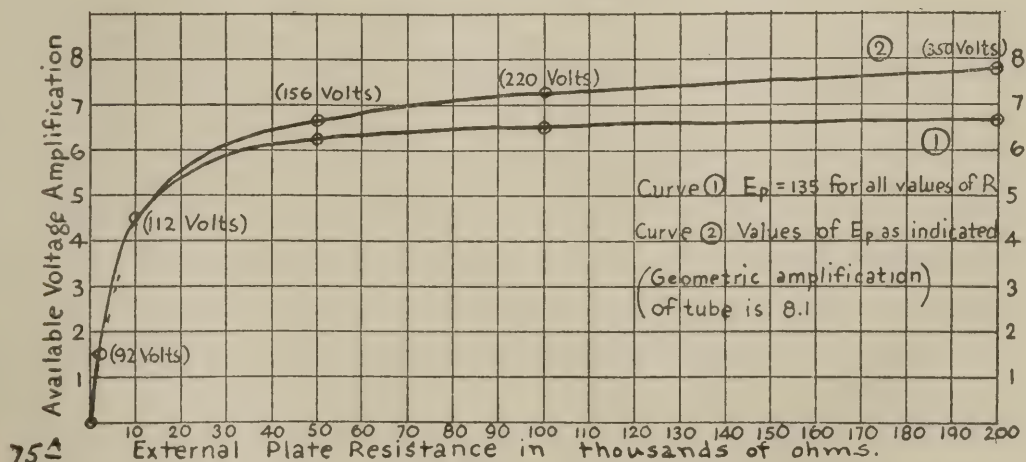


Fig. 75-a. Variation of voltage amplification with value of resistance and plate potential for a UV 201-A tube

The experimenter would do well to repeat this experiment with other values of resistance, say 2,000, 10,000, 100,000 and 500,000. In all of these cases it must be remembered that a large part of the e. m. f. of the plate battery is used up in overcoming the resistance of the resistor ($E_r = I_p R$) so that when large re-

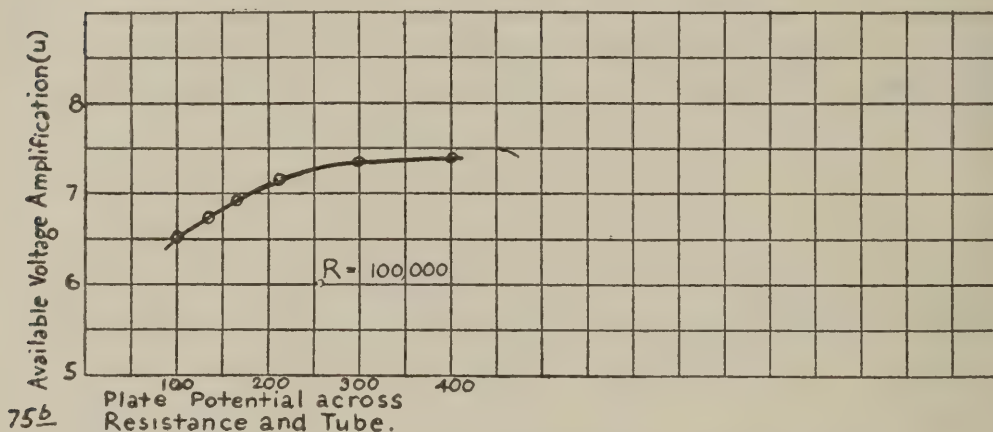


Fig. 75-b. Variation in voltage amplification with plate potential.
Plate resistance is 100,000 ohms

sistors are used the potential of the B battery must be greatly increased in order to keep the proper potential across the tube. If the above suggested experiment be carried out it will be noticed that the value of μ increases with the larger values of resistance, but that the increase for values above 100,000 is not sufficient to warrant the use of the extra B potential required. (See Figure 75a and also Figure 75b).

If the amplification factor of a large number of tubes is to be measured, a more clever arrangement of apparatus may be made, so that the value may be easily determined without drawing the characteristic curves. It is possible to make all of these tube measurements by applying alternating e. m. f.s to the grid of the tube, and since this method approaches the working conditions of the tube far better than the methods described above, it should of course be pursued in addition to the measurements already described. Some of these measurements are described further on in this chapter.

It will be well for us to consider briefly what we might expect in case of measurement with an alternating current source when we have a large inductance such as the primary of a transformer in the plate circuit instead of a high resistance. The direct current resistance of the inductance will be small, so that nearly the entire e. m. f. of the B battery will fall across the tube. Hence if we determine the characteristic curves described above we will obtain practically the same curves as we would get without the impedance. But if we determine the characteristics of the tube with alternating e. m. f.s we will get curves more nearly resembling those with direct e. m. f.s with the resistors in the plate circuit. However, if we use transformers or inductances made with a large number of turns on fairly large cores, it will be possible to greatly increase the impedance of the inductance for alternating currents without making the B battery abnormally large. Hence, it will be possible to utilize larger values of μ with inductances in the plate circuits that would be convenient with resistances.

But here it will be necessary to remember that the "impedance" of an inductance is a function of the frequency, as we have seen in a previous chapter. Hence, when we amplify audio frequencies where we have frequencies ranging from 20 to 4000 it is quite evident that the value of μ for the lower frequencies will not be as good as for the higher ones. This is one of the many reasons why the relative volume on the low tones is seldom as good as that of the middle and higher ones. If the inductance is made with a large core and a large number of turns of wire, so that the impedance for the low frequencies is large, then the difference between the values of μ for high and low frequencies will not be great. This effect is the same as the one discovered with the resistors. The value of μ increased fairly rapidly with the value of the resistance until the resistance got to be 50,000 or 100,000 ohms. Increases of resistance beyond that point were accompanied by only small increases in μ . So it follows that it is possible to make inductances and primaries of transformers which so far as the effect discussed above is concerned will give fairly uniform amplification throughout the audible frequency range needed.

Detector Action of Tubes. We have still to discuss the detector action of tubes. Let us consider the receiver circuit of Fig. 76 which we have already seen in the first chapter. To analyze the detector action of the tube in this circuit we will take one curve (the one for $E_p = 20$ volts) as shown again in Figure 77.

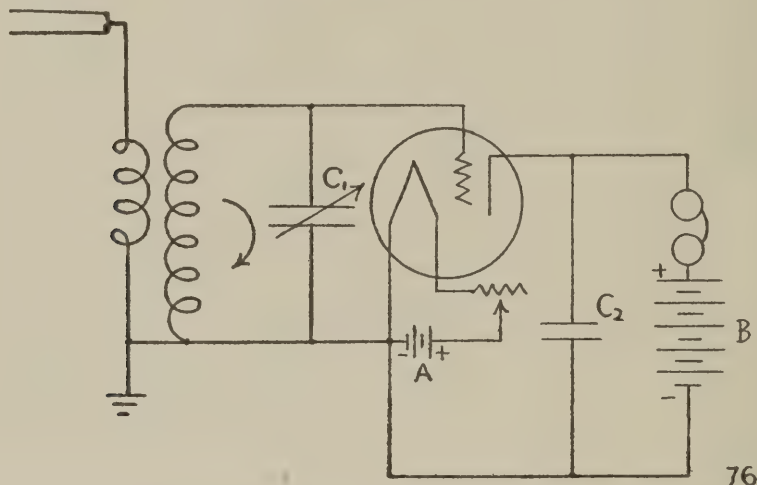


Fig. 76. Tube Detector without Grid Condenser

Suppose now that we imagine the input voltage across the grid to filament of the tube to vary between -4 and 0 due to the alternating current flowing in the tuned inductance. (The actual voltage variation supplied to a detector is much smaller than this value. The large value here used was chosen in order to make the result more evident in the figures). Before the signal came in we will suppose that the normal grid potential was -2 . If we look at Figure 77 it will be evident that when the alternating e. m. f. goes below this value, only a small reduction in the plate current can take place. But when the alternating e. m. f. goes above -2 the plate current is greatly increased. Figure 78 shows this effect on the plate current for a number of cycles of the input e. m. f. The dotted line indicates the average flow of current from the B battery during this period. It is quite evident that the actual current in the plate circuit is a direct current varying in value with the signal e. m. f. This is equivalent to the sum of an alternating current and the average direct current indicated by

the dotted line. If the high frequency e. m. f. varies in magnitude instead of remaining constant, the dotted line will also vary up and down. That is to say, the average value of the plate current will follow the variations in magnitude of the high frequency e. m. f. applied to the grid. Hence, if the incoming

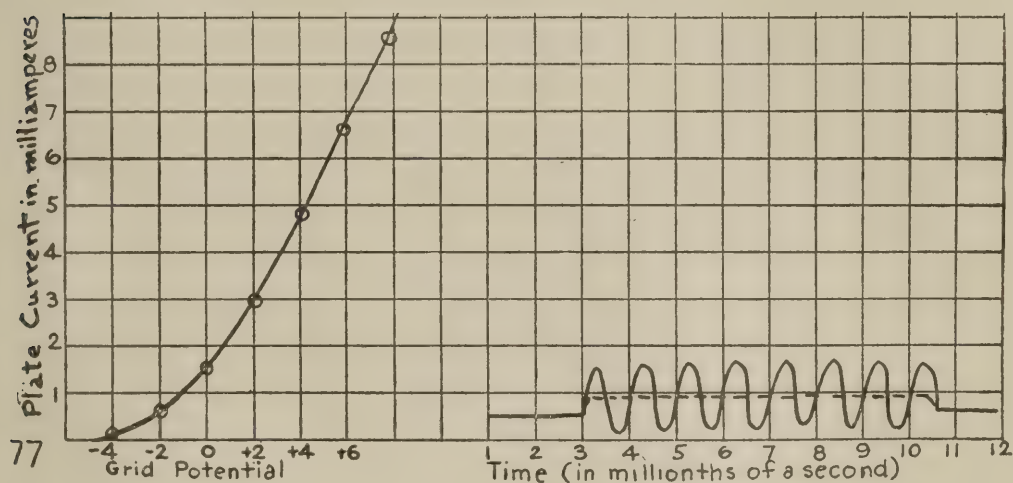


Fig. 77, 78. Detector action of a tube without a grid condenser

waves have an audible modulation, (see Figures 14 and 15) the corresponding sound will make itself evident in the telephones through the medium of the varying plate current. Meantime, a low resistance path should be offered the high frequency component of the plate current so that it will not have to flow through the high impedance offered by the windings of the telephone receivers. We have already seen that condensers offer a low impedance path to high frequency currents. The distributed capacity of the windings of the telephone receivers in part fill this need in the detector, but better results are usually obtained by using the condenser C_2 indicated in Figure 76. A commonly used value for this condenser is .002 microfarads.

One of the obvious disadvantages to this scheme for using the tube as a detector lies in the fact that the *normal* grid potential has to be very nearly the correct value if the best results are to be obtained. In some cases it may be necessary to use a C battery

on the other cycle of the high frequency e. m. f. in L_2C_1 the electrons on the tube side of the condenser are repelled into the grid, thus depressing the potential of the grid below its normal value. Of course these electrons attempt to flow back to the filament by means of the large resistance R , but the entire average

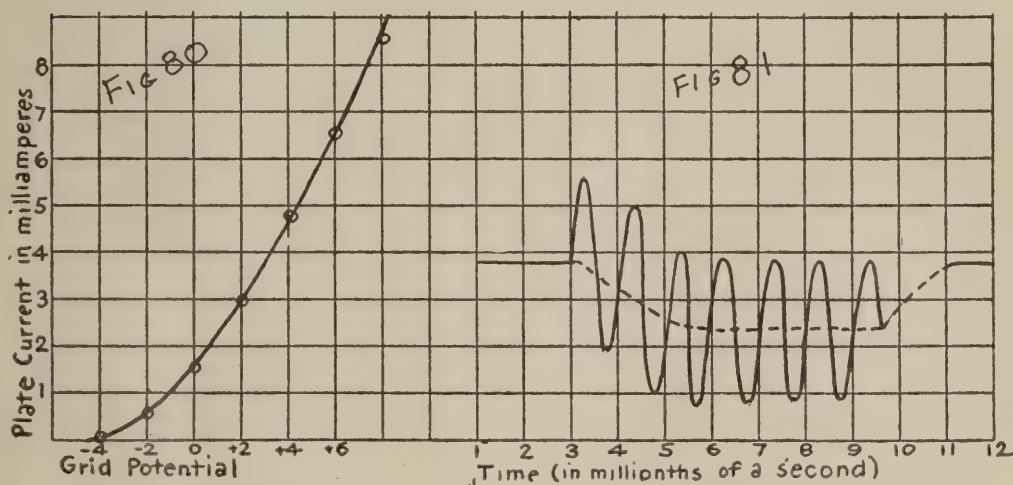


Fig. 80, 81. Detector action of a tube with grid condenser and grid leak

effect is to depress the grid potential. This effect is, of course, accompanied by a decrease in the plate current. If the incoming e. m. f. varies in amplitude then the plate current will undergo corresponding variations as indicated in the diagram of Figures 80 and 81.

Here as before one may consider the plate current to be made up of the sum of a varying plate current indicated by the dotted line plus an alternating component. For efficient operation it will be necessary to provide a low impedance path for the alternating component as was done in the preceding case. Hence we again introduce C_2 , the so-called "phone" condenser. This condenser may be used to shunt the telephone receivers only or it may shunt both the telephone receivers and the B battery. The latter method seems to be coming into more common practice of late since most of the condensers nowadays are well enough made so as not to short circuit the B battery because of leakage in the condenser. Also, in multi-tube sets it is considered desirable to keep the high

frequency currents out of the B battery in order to eliminate coupling between the circuits of the various tubes.

It is quite evident that the exact location of the normal grid potential is not nearly so critical for the grid condenser method of detection as for the method first described. The only requirement is that the normal potential be so located that the grid variations of e. m. f. do not extend beyond the nearly straight part of the curve of Figure 80. It is interesting to note that detection by the first method involves an increase in plate current when a signal comes in while detection by the condenser method involves a decrease. However, when no signal is coming in, the normal plate current is less for the first case than the second. The fact that maximum efficiency of detection can be obtained with the grid condenser method without much care as to the exact normal grid potential has brought this latter method into almost universal use. Also, for most tubes, the detecting efficiency of the grid condenser method is greater than that of the other method even when the normal grid potential is correct.

For the student who wishes to go further into the theory of tube detection and into calculations for the proper size of grid condensers and grid leaks, references are given at the end of this chapter. Sizes of condensers and grid leaks for use with detecting tubes are now determined by the manufacturer of the tubes and the information is to be found on the carton or on a circular accompanying each tube.

Dynamic Characteristics of Tubes. The discussion of tube characteristics given in this chapter has been based largely on effects with steady rather than with alternating currents and e. m. f.s. Since, however, tubes are used with alternating e. m. f.s applied to the grids it seems advisable to measure such quantities as the amplification factor under conditions approximating those of actual use.

In addition to knowing the amplification factor of tubes, it is useful to know the alternating current resistance of the internal plate circuit of tubes. The smaller this value is the more power

the tube can handle—other conditions being equal. Moreover, transformers and loud speakers give best performance when their impedance is, for tones in the middle of the frequency range to be handled, equal to the alternating current resistance of the tube.

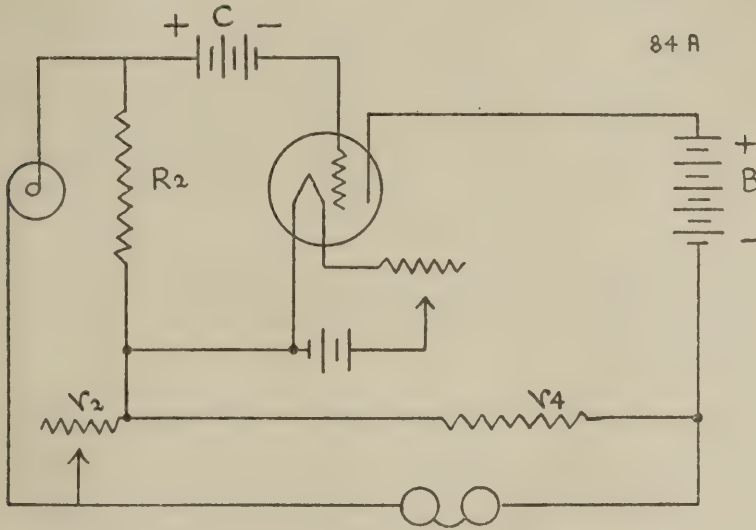


Fig. 84-a. A Circuit for Measuring Mutual Conductance

Mutual Conductance. A third quantity which serves to connect the voltage amplification of a tube and its alternating current resistance is known as the mutual conductance. This quantity is fairly easy to measure and is, in general, a good indication of the merits of the tube. The mutual conductance of a tube is really the ratio between the changes in plate current and the applied potentials of the grid. It happens to be equal to the voltage amplification factor divided by the internal resistance thus:

$$G_m = \frac{\mu_o}{R}$$

where G_m is the mutual conductance, μ_o the voltage amplification factor and R the alternating current resistance of the tube.

In Figure 84-a we have a simple circuit for determining the mutual conductance of tubes. R_2 is a 1,000 ohm resistor. r_4 is

100 ohms and r_2 is a variable resistance. For precise measurements a good resistance box should be used for r_2 ; but for approximate values a potentiometer of 200 ohms connected as a rheostat instead of as a potentiometer may be used. Observe the distance the dial travels in going from the beginning to the end of this rheostat. Divide this distance on the dial into 20 equal parts. If these divisions were marked 10, 20, 30, etc., they would indicate the resistance of the rheostat in ohms for the various settings. If, however, we mark these divisions 100, 200, 300, etc., up to 2,000 the dial of the rheostat will read directly the value of the mutual conductance.

The oscillator S may be a laboratory microphone hummer or it may be the buzzer described earlier for use with an alternating current bridge.

r_4 and R_2 are left at the fixed values given above. r_2 is varied until the sound in the telephones is a minimum. The reading on the dial of r_2 is then the mutual conductance of the tube in terms of micro-mhos, i. e., millionths of plate circuit amperes per volt of grid potential.

Even if the calibration of r_2 is rather poor, so that the actual value of the mutual conductance is not given very precisely, the instrument is still valuable for the comparison of tubes both for purposes of picking out those with high values and those with low values and also for matching tubes so as to be able to pick out a group having the same value.

In all cases the value of plate potential and grid bias should be the same as those with which the tube is to be used.

Voltage Amplification Factor. Figure 84-b shows a circuit to be used for measuring the voltage amplification factor of tubes. r_1 is kept at the constant value of 10 ohms. r_2 is a 200 ohm potentiometer connected as a rheostat as in the previous case. However, instead of marking the dial divisions as before they are marked 1, 2, 3, 4, etc., up to 20. This dial will now read the voltage amplification factor directly. The resistance r_2 is adjusted to give a minimum of sound in the telephone receivers.

The above methods of measurement have been taken from H. J. van der Bijl's book on *Thermionic Vacuum Tubes*, pp. 203-205. A more extended discussion of tube measurements may be found in this same reference.

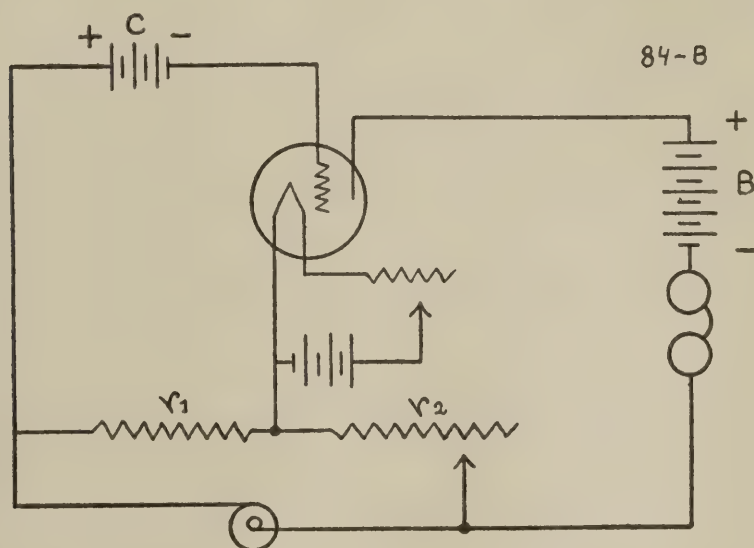


Fig. 84-b. A Circuit for Measuring the Voltage Amplification of Tubes

Alternating Current Resistance. When both the voltage amplification of a tube and its mutual conductance are known, the alternating current resistance can be calculated from the relation

$$R = \frac{\mu_o}{G_m} \times 1,000,000.$$

R will be given in ohms if G_m is in micro-mhos as before.

Example.

An old UV 201-A tube was measured by the above described methods when the plate potential had a value of 90 volts and the

C battery bias was 4.5 volts negative. These measurements gave

$$\mu_o = 7.7$$

$$\text{and } G_m = 580 \text{ micro-mhos.}$$

Therefore

$$\begin{aligned} R &= \frac{7.7}{580} \times 1,000,000 \\ &= 13,280 \text{ ohms} \end{aligned}$$

This is a somewhat larger value of tube resistance than is shown by the average UX 201-A tube when new.

Regeneration and Regenerative Circuits. In the first chapter we were introduced to the fundamental idea of regeneration, namely the feeding of electrical energy from the output circuit of a tube back into the input. We might consider again the circuit shown in the first chapter. (See Figure 82). The circuit is exactly like that of Figure 79 except that the plate circuit has been opened and the "tickler" coil T inserted. If our analysis of the previous circuit was correct, we will have flowing in the plate circuit a rapidly varying current which may be resolved into a direct current and an alternating current. The tickler coil will carry this entire current. The direct current will pass through the telephone receivers as before and the high frequency current will be bi-passed around the telephone receivers by the phone condenser. (Of course when the incoming signal is modulated the average direct current here referred to will vary according to the audio modulation as described before).

We have seen that when the current flows steadily through coils that are close together, no effect is produced in either circuit by the presence of the other. However, when the current in one of the coils undergoes changes, e. m. f.s are induced in the neighboring coil. Hence we may expect to have induced e. m. f.s in the coil L_2 due to the high frequency component of the current flowing in T. Now these induced e. m. f.s in L_2 may be in phase with those of the original signal or they may be just reversed, depending on

the relative directions of winding of the two coils. If the induced e. m. f.s are in phase with the original e. m. f.s the effect will be to increase the current flowing in the tuned circuit $L_2 C_1$. Of course, there is at the same time an increased alternating e. m. f. across the terminals of L_2 and hence the e. m. f. applied across the tube

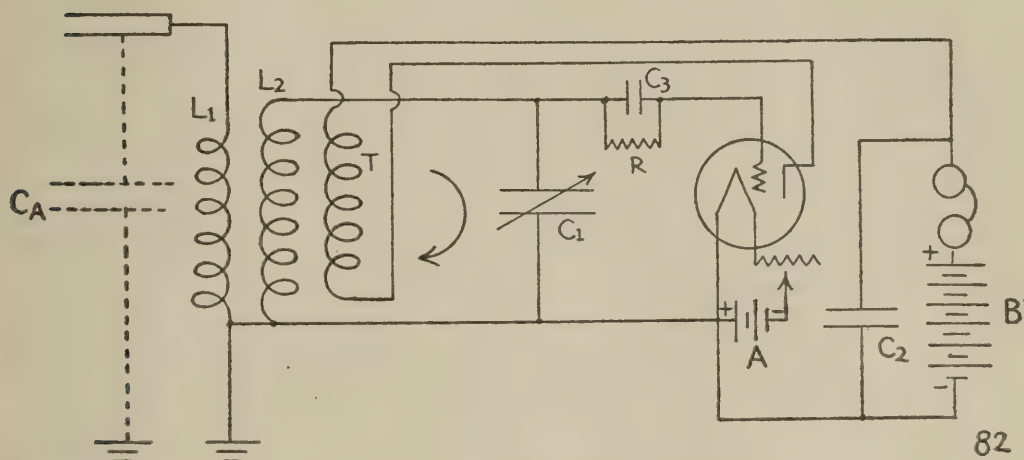


Fig. 82. A Regenerative Receiver. Energy from the output circuit is fed to the input through magnetic coupling between T and L_2

between the filament and the grid is increased. Such a state of affairs must result in increased amplitude of the changes in the plate current. These increased changes, in turn, induce still larger e. m. f.s in L_2 . The process described is known as regeneration. If the coil T is too large or if it is placed too close to L_2 the e. m. f.s induced in L_2 will be of such magnitude as to maintain alternating currents in the circuit $L_2 C_1$ independent of the relatively feeble currents flowing in the antenna circuit from the broadcast signal. The tube and its circuits are now said to be in a state of oscillation with the frequency of oscillation fixed by the tuned circuit $L_2 C_1$. This arrangement of tube, batteries, condensers and inductances may be used as a generator of high frequency currents and may be used for transmitting purposes. Arrangements for feeding energy from the output to the input circuit of a tube other than the method outlined above are numerous and we shall discuss two others, after finishing with some details of this one in its use as a detector rather than an oscillator.

When regeneration takes place we have seen that the amplitude of the radio and hence of the audio variations in the plate circuit are greatly increased so that we may expect a great increase in the volume of sound from the telephone receivers. The effect is greatest for the regeneration which places the tube just on the verge of oscillating. Also the selectivity of the set is increased by the regeneration, for the effects of the regeneration may be thought of as lowering the resistance of the tuned circuit $L_2 C_1$ and also that of the antenna circuit for the one particular frequency for which the circuit $L_2 C_1$ is adjusted. But if we refer to the first chapter we will see that too high a degree of selectivity is not desirable, since it will not permit all of the side-bands to pass. Our great increase of volume is therefore accompanied by a certain loss in the high tones. This effect is not great enough to be objectionable for small amounts of regeneration, but is decidedly so when the set is brought near the condition for oscillations.

The diagram indicates that the antenna coil L_1 is smaller than the coil L_2 and that its amount is not variable. A few years ago it was customary to make this coil larger and to arrange a series of connections to it, so that by means of a multiple point switch a greater or less amount of the coil could be used. This scheme gave the possibility of a moderate amount of tuning in the antenna circuit, but the increased selectivity of the receiver and the slightly increased volume did not prove to be sufficient to compensate for the increased difficulties of tuning. The same station could be brought in at different settings of C_1 if different taps on L_1 were used. In the average set of this kind today the coil L_2 , if wrapped on a tube of three inch diameter, may have as many as 60 or 70 turns; whereas L_1 will usually have but 12 to 15 wrapped on the same tube and at a little distance, say half an inch from the end of L_2 . L_1 is occasionally wrapped on top of L_2 . This scheme tends to increase the volume but to reduce the selectivity to the point where it is difficult to tune out local stations.

Aperiodic Antenna Circuit. We have already spoken of the "antenna circuit." If we consider the antenna to ground capacity as indicated in Figure 82 it is justifiable to consider this as a complete circuit for alternating currents, where the resonant frequency

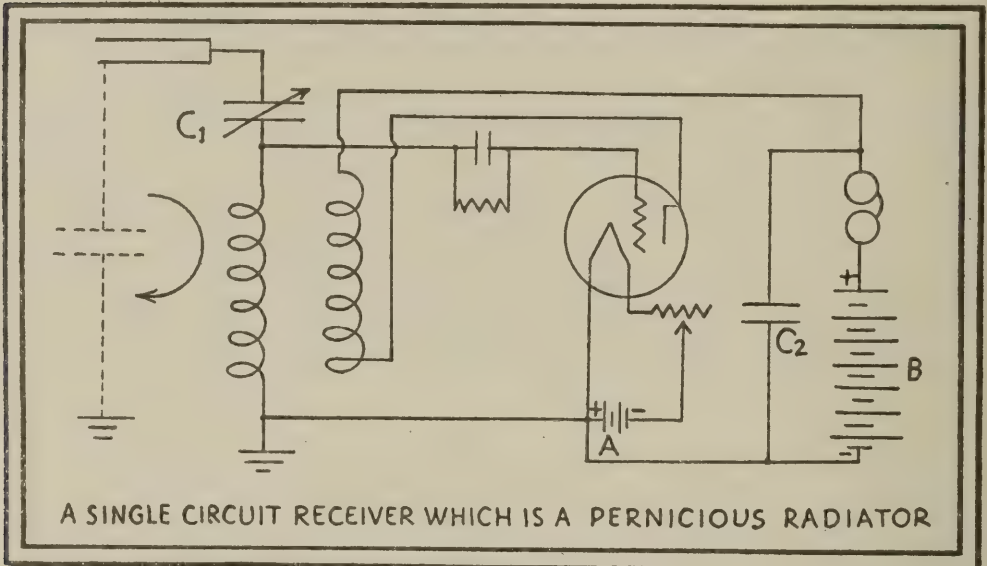
is fixed by the capacity of the antenna to ground (indicated by the dotted lines) and the inductance of L_1 . If L_1 is made small, as indicated above, so that the product of L_1 and C_A is considerably smaller than the value required to make the circuit resonant at the broadcast frequencies, it is sometimes called an "aperiodic" primary.

In addition to the ease of tuning gained with the so-called aperiodic primary, there is another advantage that is of more interest to one's neighbors than to the operator himself. If the antenna circuit is not tuned, then when the circuit $L_2 C_1$ goes into oscillations due to over-regeneration, smaller currents will flow in the antenna circuit due to the oscillations in this circuit than if the antenna circuit were a tuned one. Hence less energy will be radiated and the disturbance to other listeners will be less than with a receiver employing a tuned antenna circuit.

Radiating Receivers. In the early days of broadcasting, a certain simple type of receiver in which the only tuned circuit was the antenna circuit became quite popular because of the low cost of the receiver and the simplicity of tuning. Figure 83 properly draped in mourning to show that the circuit should be (whether it is or not) dead and buried, illustrates the general principle involved. The set can be re-drawn in many ways and camouflaged and given fancy names, but whenever the set is regenerative and the antenna circuit is the principal tuning circuit, you can depend on it as being a strong radiator. Some years ago we were so charitable as to think that such a set only disturbed listeners within a radius of a few blocks. But tests carried on in Cleveland and vicinity a year or so ago indicated that the disturbance may extend up to distances of five to fifteen miles.

When one is tuning any form of regenerative tuner, the most simple way to locate a station is to turn the tickler coil until the set oscillates. The condenser is then turned back and forth until a shrill note is picked up. Further turning the condenser causes this note to become lower in frequency until it vanishes entirely. Still further turning in the same direction causes a rise in frequency

until finally the note is so high as to be no longer audible. The note that one hears is the "beat" or difference note between the frequency of the station and the changing frequency of the local oscillator. The proper setting of the condenser is in the middle of the squeals, that is, in the position of zero beat frequency. As



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Fig. 83

soon as the station is located the tickler coil is turned back and the capacity C_1 re-adjusted. If even fair quality is expected with the average tube, the tickler must be turned back until the set no longer oscillates. All of the whistles heard by the operator are heard by every other person in the vicinity who happens to be trying to listen to the same station.

When one is listening to a local station it is not at all necessary to use the above method for locating the station, since the signal can easily be brought in when the regeneration is nowhere near the spilling over point. There is a great tendency on the part of owners of regenerative sets to try to bring in the most distant stations. These efforts result in making the set spill over the oscillation point numerous times, and in turning the condenser back and forth endlessly while the set is in this condition. The signal

is frequently so weak that the regenerative set will not be able to get it and maintain even fair quality, and in the meantime reception is ruined for people with more powerful types of receiving equipment.

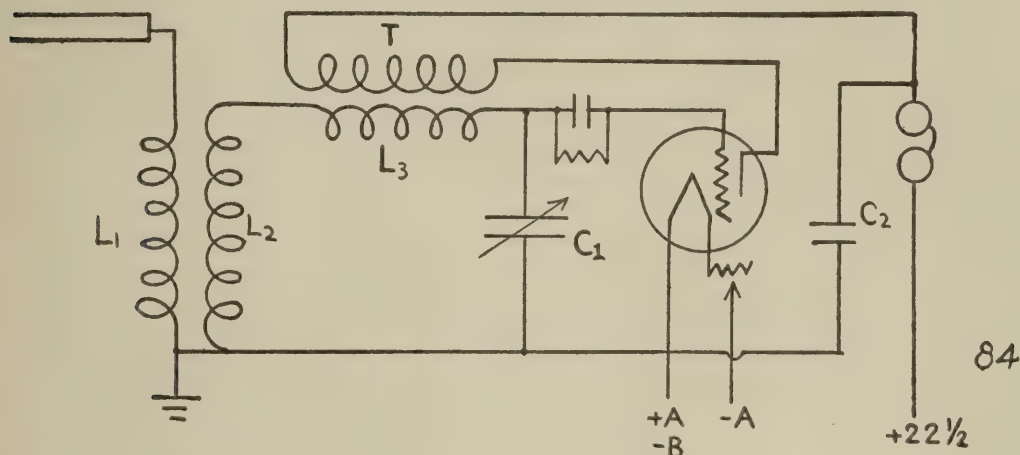


Fig. 84. A Regenerative Circuit in Which the Tickler Coil Has no Direct Magnetic Coupling with the Antenna Circuit.

In spite of these many just criticisms of the use of regenerative receivers, it is necessary to admit that for the amount of equipment involved they offer the most efficient means of reception. In Figure 84 we have a circuit that offers some slight improvements over any of the others shown. It employs the untuned primary as does the circuit of Figure 82. The secondary is divided into two parts with about 50 turns on a three inch tube for L_2 and about fifteen turns on the same size tubing for L_3 . L_1 and L_2 may be wrapped on the same tube, but L_3 should be placed at right angles to L_1 and L_2 so that the magnetic field of T will not induce currents in them directly. This arrangement seems to be slightly more satisfactory than the more simple arrangement of Figure 82. Note that the coils L_1 and L_2 are fastened together and that the rotor side of the condenser C_1 is the one fastened to the grounded side of L_2 . Best results are obtained with most tubes now on the market when the grid return is made to the positive side of the filament if the grid condenser method of detection is used.

In Figure 84 and in many of the figures that follow the batteries are omitted from the diagrams and the connections to the proper binding posts indicated.

Even the circuits of Figures 82 and 84 will radiate to some extent if they are forced to oscillate. Regeneration is used in many of the more complicated sets now in common use, but in these it is so used as not to be able to radiate energy into space. The principle, however, is of such great importance that it has seemed advisable to discuss at some length the use of regeneration in simple receivers.

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SIMPLE RECEIVING CIRCUITS
AUDIO AMPLIFIERS

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CHAPTER VI

Simple Receiving Circuits Audio Amplifiers

A CONSIDERABLE part of the last chapter was spent in a discussion of regenerative reception where the regeneration was accomplished by magnetic coupling between the output and input circuits of the detecting tube. In the first part of this chapter we shall consider two other methods of obtaining regeneration. The first of these is important because it occurs in an undesirable way in tuned radio frequency sets and our problem there will be to eliminate it. The second method is important because of its several applications to superheterodyne receivers.

Regeneration Through Tube Capacities. The underlying principle of the first of these methods can be determined from a study of a receiving circuit that was once popular under the name of "Paragon." Figure 85 shows the earlier form of this circuit and Figure 86 a later modification that seemed to operate a little better. Both were very efficient regenerative detectors, but they lost their popularity because of the technique required to tune them.

Let us consider the internal construction of an ordinary three-electrode tube. We have a metal filament surrounded by a metal mesh-work called a grid and this entire structure surrounded by a sheet of metal called a plate. It is then reasonable to think of the filament and grid forming the two plates of a very tiny condenser. Similarly the grid and plate form another tiny condenser. We can think of these two condensers as being in series to make a closed circuit for alternating currents of any plate circuit, such for instance as the plate circuit of Figure 85. We

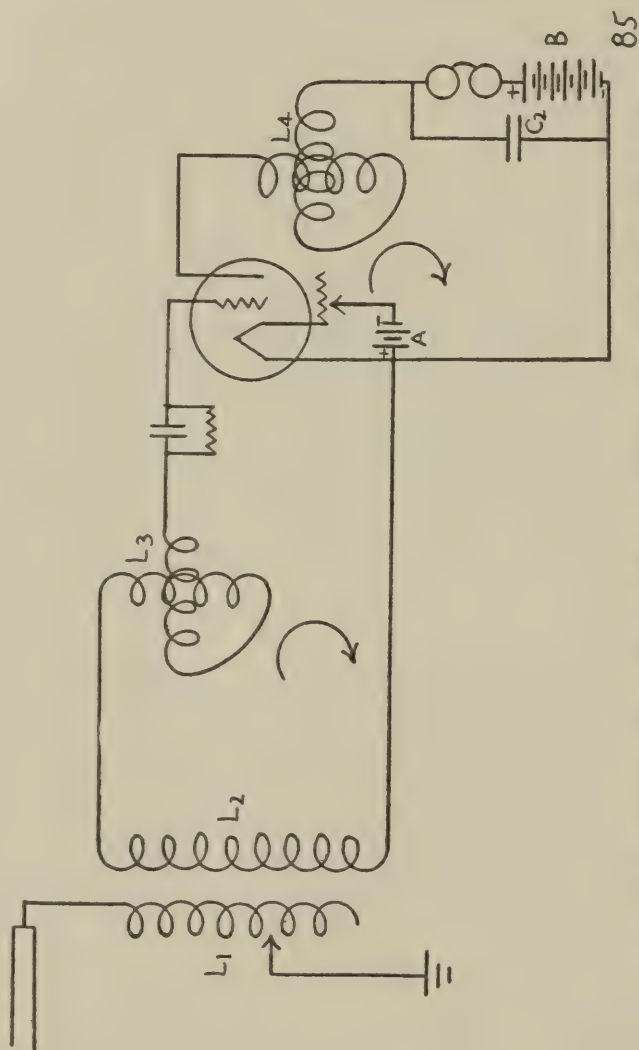


Fig. 85. A Regenerative Circuit in Which Energy from the Plate Circuit is Fed Back to the Grid Circuit through the Capacities of the Tube Elements.

might draw this circuit in the manner of Figure 87. Similarly we may redraw the grid circuit, and this has been done in Figure 88.

Because of the particular arrangement of the parts of the tube we can also think of the filament and plate constituting a con-

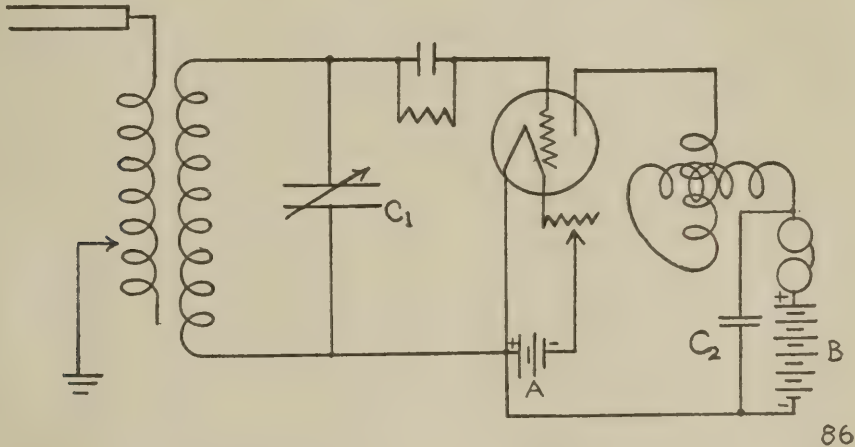


Fig. 86. A Regenerative Circuit Similar to the Preceding One Except that the Tuning of the Input Circuit is Accomplished by Means of a Condenser Instead of a Variometer

denser independent of the grid. This condenser will be smaller than the others because the filament and plate are relatively far apart, and we shall neglect the effect of this tiny capacity in our present discussion.

If we consider the circuits of Figure 87 and Figure 88 it will be apparent that the filament to grid capacity which we shall call C_g is common to both. We will then combine these two circuits in the manner in which they actually exist as shown in Figure 89.

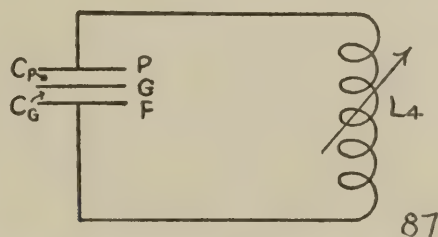


Fig. 87. Schematic Drawing of the Plate Circuit of the Preceding Diagrams.

If we refer to Figure 85 we can see that the first section of the circuit of Figure 89 is made up of L_2 and L_3 in series with C_g , and the second circuit section of L_4 and C_g and C_p in series. Let us suppose that the values of L_3 and L_4 are so adjusted that each circuit is tuned to the same frequency. In actual operation alternating current flowing in the antenna circuit in-

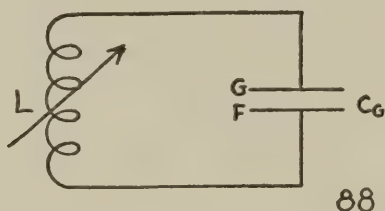


Fig. 88. Schematic Drawing of an Input Circuit.

duces e. m. f.s in the first of the above circuits and causes a current to flow in this circuit. The e. m. f. existing across C_g will be proportional to this current and inversely proportional to the size of the condenser C_g . We have already seen that when an alternating e. m. f. exists across C_g the plate current can be considered to consist of a direct current plus an alternating current. In the diagram of Figure 89 we shall be concerned with the alternating component. (Of course the fact that electrons are flowing from the filament to the grid should introduce some of the complications of a leaky condenser for C_g , but we are not primarily concerned with that effect here).

So when an alternating current flows in the first circuit, a larger alternating current flows in the second (or plate) circuit of Figure 89. Such a current will give rise to an alternating e. m. f. across the two condensers in series C_g and C_p . If this current across C_g is in phase (or nearly so) with the e. m. f. supplied across the same condenser by the input circuit then we have the necessary conditions for regeneration, namely, feeding energy from the output circuit to the input circuit in such a manner as to aid the current flowing there. If the two circuits are tuned to the same frequency we find that regeneration takes place. In fact the two circuits tend to oscillate. Regeneration is usually controlled in this type of set by varying the current through the filament. Varying the

current through the filament varies the number of electrons freed and changes the slope of the grid potential-plate current curve. It is evident that if this slope is made less than normal for the tube, the amplitude of the alternating current in the plate circuit will be less for a given applied e. m. f. across the filament to grid

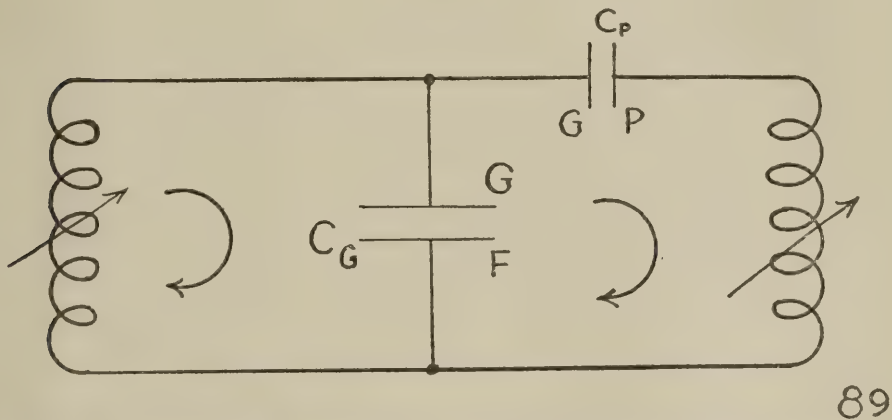


Fig. 89. Schematic Representation of the First Circuit in this Chapter.

than under normal conditions. Hence the tendency to oscillate will be reduced.

In the original sets tuning of the two circuits was accomplished by the use of variable inductances called variometers. Later a condenser tuned input as shown in Figure 86 was substituted for the variometer. The precise analysis of this circuit is slightly more complicated due to the condenser; but the method of feeding back energy through the medium of the tube capacities is the same.

In a later section on coupled circuits we shall go a bit further into the effects of condensers in the external circuits. The regenerative effects due to tube capacities is the source of the major difficulties in building tuned radio frequency sets, and it is for this reason that this simple analysis of the circuit of Figure 85 has been given here. We shall study the effects of tube capacities as illustrated in Figure 89 in the section on tuned radio frequency receivers.

Regeneration—Hartley Method. We come now to the last of the regenerative circuits to be considered here. The circuit is shown in Figure 90. Tuning is accomplished by means of the condenser C_1 and the amount of regeneration is controlled by the condenser C_2 . If the condenser C_2 be made

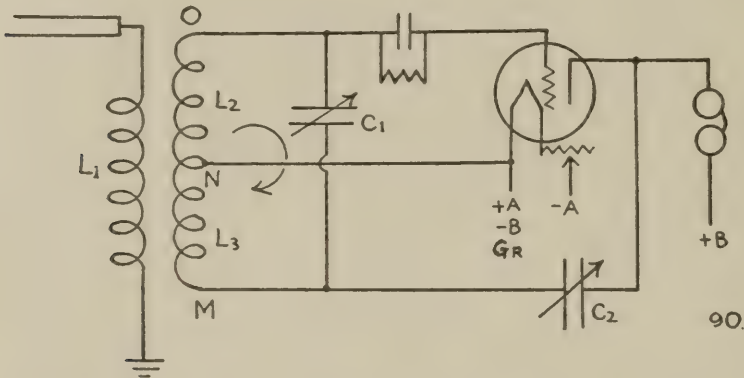


Fig. 90. "Hartley" Type of Regenerative Detector where the amount of feedback between the input and output circuits is controlled by the small condenser, C_2

large so that it offers little impedance to the flow of high frequency currents through the circuit from the plate to the filament through C_2 and L_3 , then we have a very good oscillating circuit. In fact this is one form of the well known Hartley circuit in common use as a transmitter.

The tuned circuit consists of the condenser C_1 and the entire coil $L_2 L_3$. Now it is possible to pick out any two points on a tuned circuit and excite the circuit by applying e. m. f.s of the proper frequency between the two points. The points chosen in this case are M and N. The direct current part of the plate current flows through the telephone receivers (which act as a choke coil), while the alternating current component of the plate circuit flows through the relatively low impedance path offered by $C_2 L_3$. Since, however, L_3 offers some impedance to the flow of alternating current we get an e. m. f. equal to the product of the alternating current and this impedance applied across the terminals M N. In this method oscillating currents are established in the tuned

circuit. These of course build up the e. m. f. across L_2 and so give greater amplitude to the grid potential variations. These in turn cause an increase in the alternating current component of the plate current, and so we have a self-excited, i. e., an oscillating, tube circuit.

If now, the value of C_2 be decreased the impedance of the circuit $C_2 L_3$ will increase and thus cause a decrease in the alternating component of the plate current that flows through this circuit. When this current has been decreased sufficiently, the e. m. f. due to it across $M N$ will be so low as no longer to maintain the oscillations in the tuned circuit. The set will then be regenerative, but not oscillatory. The limiting condition for oscillations in this circuit is that the energy fed into the tuned circuit from the plate circuit shall be sufficient to supply the losses of that circuit. The heating loss $I^2 R$ is one of the principal losses in the circuit, although the presence of the antenna coil and circuit offers another source of loss. The tap to the filament should be made so that

$$L_2 = \frac{2}{\mu_o} L_3$$

where μ_o is the theoretical amplification factor of the tube. For an ordinary 201-A tube this means that L_2 should be about one-fourth of L_3 . The exact location of this tap, however, is not at all critical. This circuit is introduced here because of its use to gain regeneration in sets employing loops instead of antennas and because of its further use as a generator of alternating currents in superheterodyne receivers.

Audio Amplification

In the first chapter we discussed at some length the complex nature of the sound which we expect to be perfectly transmitted and reproduced by radio devices. We saw that in music we meet with tones some of which have very low frequencies, (16 per second for the lowest note of a large pipe-organ), and others which have relatively high frequencies. The highest note on a piano has a fundamental frequency of over 4,000.

In almost all the problems of electrical power engineering we are concerned with only one frequency of current at a time. All of our transformers and most of our motors are built to operate on some one frequency of current. But when we come to radio apparatus we want a single piece of apparatus to handle with equal efficiency currents throughout an unreasonably large frequency range.

We will at this point consider the modulation of the incoming carrier wave to be a true representation of the original sound. Moreover we will consider the detector circuit to be capable of reducing the high frequency modulated currents to audible currents without distortion. This latter assumption is a reasonable one provided the impedance of the telephone receivers be large for even the lowest frequencies of the original sound. We will now be concerned with taking this nearly perfect set of alternating currents from the plate circuit of the detecting tube and amplifying all of them equally up to the point where sufficient energy can be expended through the medium of a loud speaker to give a fairly large amount of volume.

There is just one method for obtaining power from the plate circuit of a tube, and that is by the introduction of an impedance in the external part of that circuit. Since some part of this circuit must carry the steady plate current the impedance can not consist of a condenser but may consist of either a resistance or an inductance. The inductance may or may not be the primary of a

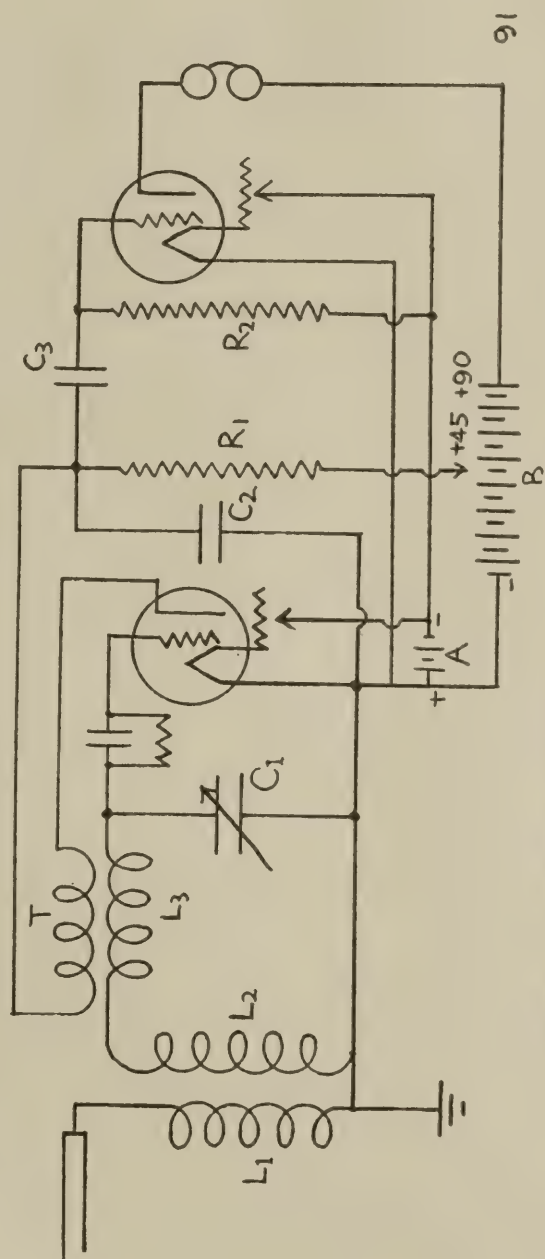


Fig. 91. One Stage of Resistance Coupled Amplification added to a Simple Regenerative Detector

transformer. We shall consider the most simple case first, namely, that of introducing resistance.

Resistance Coupled Amplifiers. For simplicity let us take the regenerative circuit of Fig. 84 and substitute a 100,000 ohm resistor for the telephone receivers. C_2 is the condenser which permits the high frequency currents to have a low impedance path in the plate circuit of the detector tube. This condenser must be kept small, however, say .001 mcf., so that it does not permit an appreciable amount of the low, or audible, frequencies to be bypassed in this manner. The varying plate current through R_1 gives rise to changes in potential across R_1 equal, according to Ohm's law, to the product of the changes in current and the resistance R_1 .

$$dE = R_1 dI$$

dE is the change in potential across R_1 and dI is the change in plate current. These alternating potentials will be impressed on the grid of the second tube in Figure 91. Corresponding audio frequency changes will take place in the plate current of this tube and these changes will be of greater amplitude than those occurring in the first tube. In fact, as we have seen in the fifth chapter, the available voltage change across the telephones shown in the figure will be μ times the available change across R_1 .

In some respects the input circuit of the second tube of Figure 91 resembles that of a detecting circuit, and the question arises as to whether or not there is any rectifying action of the tube on the audio frequency currents. The potential of the grid is depressed as in the case of the detector, but the variations so produced in the plate current would be too slow to give an audible sound in telephone receivers placed in that circuit. In this type of amplifier the grid condenser is used to permit the passage of alternating e. m. f.s to the grid of the next tube, and at the same time to keep the high plate potential off of the grid.

The grid leak R_2 becomes necessary in this case as in the case of the detector with grid condenser in order that the normal

value of the grid potential may be controlled. For the first stage of an amplifier, R_2 may be quite large, say 1,000,000 ohms.

Size of Condensers and Grid Leaks. The voltage changes supplied to the circuit of this amplifier are impressed across C_3 in series with C_g and R_2 in parallel. This circuit is indicated schematically in Figure 92. It is evident that part of the e. m. f. falls across C_3 and part across C_g and R_2 . Only this latter part is available for operation of the amplifier tube. It therefore follows that the potential drop across C_3 must be made as small as is practicable. This result can be obtained by making C_3 very large in comparison with C_g .

Whether or not C_3 is made large in comparison with C_g the relative value of the e. m. f. used up across C_3 and C_g would be the same for all frequencies were it not for the presence of R_2 . In other words, although greater amplification will be obtained with a large value of C_3 , uniform amplification over the entire audible frequency range would be obtained for any value of C_3 were it not for the presence of R_2 . However, as in the case of the detector circuit, it is necessary to have a grid leak in order that the electrons which collect on the grid of the tube may leak back to the filament. Otherwise the grid would take on a permanent negative potential of such magnitude as to interfere with or even stop the plate current. The greater the variations of grid potential the greater the number of electrons attracted to the grid. From this consideration it follows that in a train of amplifying circuits of the type of Figure 91 successive grid leaks must be made smaller because of the larger grid alternating e. m. f.s. as we go from stage to stage of amplification. In fact an amplifier often goes dead for an instant if an extremely large e. m. f. strikes it, due to the fact that the grid leaks for normal load do not permit the grid condensers to discharge rapidly enough. The amplifier is then said to "block." Since grid leaks are a necessity, we shall analyze roughly the relations between amplification, frequency, and size of grid condensers when grid leaks of the proper size are used.

Analysis of Resistance Coupled Amplification.

If we again refer to Figure 92 we can see that when an alternating e. m. f. is applied between the points A and B the current which flows in this circuit will not be in phase with the e. m. f. but will lead it according to the discussion of Chapter IV. Moreover, the

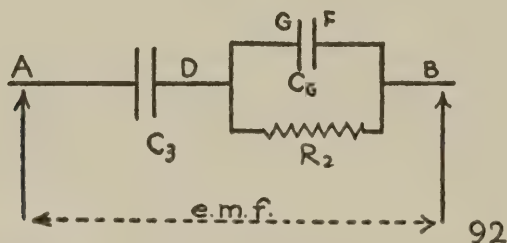


Fig. 92. The alternating e. m. f.s from the detector are applied across C_3 in series with C_g and R in parallel in the case of resistance coupled amplification

e. m. f. across A D will not be in phase with that across D B because the circuit A D contains capacity only and the circuit D B contains capacity and resistance in parallel. These facts must be taken into consideration when one attempts to determine what fraction of the total applied e. m. f. is available across the condenser C_g for the operation of the amplifier tube. The calculations needed are best accomplished through the use of complex arithmetic as taught in courses in alternating currents. The solutions are somewhat beyond the scope of this text, but the results of such calculations are shown graphically in Figure 93.

When resistance coupled amplifiers were written up by the popular radio magazines two or three years ago, nearly all of the articles showed the value of C_3 to be .006 mcf. That this value is much too small is shown by the curves of Figure 93. In these curves it has been assumed that C_g is about 50×10^{-12} mcf., which is the right order of magnitude for the average small tube. The graph shows clearly that when a large grid leak is used in connection with C_3 equal to .006 mcf., the amplification is fairly uniform down to a frequency of about 100. There we have 97%

of the original e. m. f. available across C_g . At f equals 50 we have 89% and for lower frequencies the available fraction decreases rapidly.

If now we find it necessary to use a grid leak of only 250,000 ohms in order to increase the stability of the amplifier we find that for a frequency as high as 400 we have only 96% of the e. m. f. across C_g . The available fraction becomes smaller rapidly so that at a frequency of 25 we have only 23% of the e. m. f. across C_g .

These effects are of more importance than is at first apparent. If we use three amplifier tubes using grid leaks of 1,000,000, 500,000 and 250,000 in the first, second, and third tube circuits respectively, then finally the volume of a note of frequency equals 100 as compared to the high notes would be given by

$$.97 \times .86 \times .69 = .58$$

and for a note of frequency 25

$$.69 \times .50 \times .23 = .08.$$

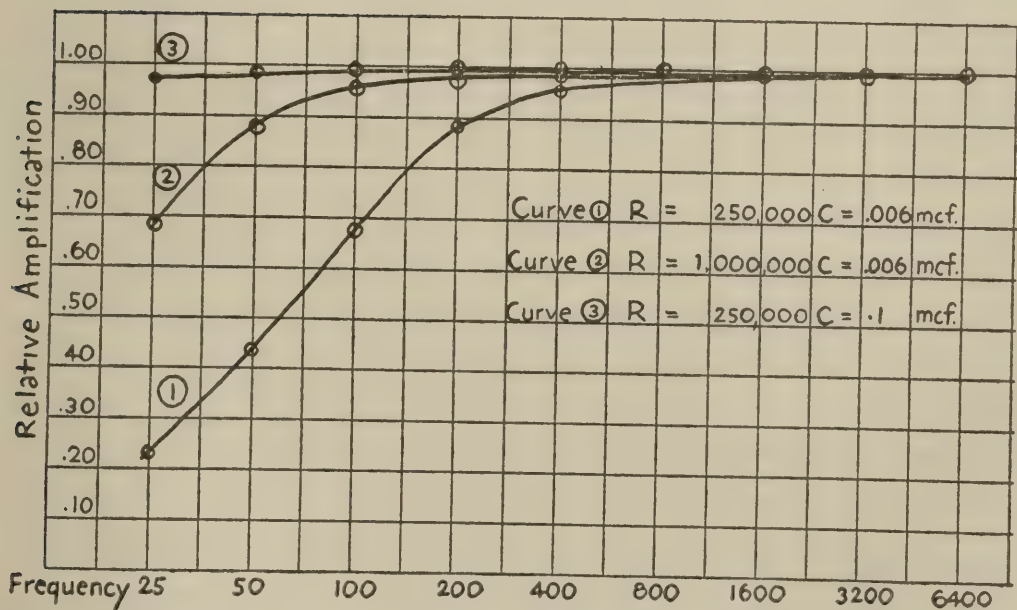


Fig. 93. Effect on amplification of various sizes of coupling condensers and grid leaks

It is quite evident that the low notes of bass viols and pipe-organs will be almost entirely lost and drums will be both faint and displeasing.

On the other hand we see at the top of Figure 93 the curve for a condenser of 0.1 mcf. and grid leak of 250,000. For a note as low as 25 the e. m. f. across C_g is 97% of the whole. Of course the curve would be even better for larger values of grid leaks.

If very perfect reproduction is desired still larger condensers may be used, but the use of too large condensers makes it necessary to use somewhat smaller grid leaks, so that not much is gained. A slight gain results in using 1.0 mcf. condensers and many broadcasting stations use either 1.0 or 2.0 mcf. condensers in their audio amplifiers.

Number of Stages in a Resistance Coupled Amplifier. We have seen in Chapter V the maximum value of voltage amplification across a resistance used with a 201-A type of tube is about 6. It is therefore evident that we shall require at least three and probably four stages of amplification to build up the signal from the detector to loud speaker dimensions, unless tubes with larger values of μ_o are used.

Figure 94 shows a standard three-stage amplifier of the type discussed above. The sizes of condensers and resistances ordinarily used are given in the figure. The figure shows a separate grid return for the last tube, in case that tube should be a different type than the others.

In purchasing resistances for such an amplifier it is well to remember that the plate resistors must be constructed so as to be able to carry the plate current of each tube without overheating or causing a change in the value of the resistance.

C Batteries and Resistance Coupled Amplifiers. In the figure the filament ends of the grid leaks are shown to connect to the negative end of a C battery. However, it is quite customary to connect this lead directly to the negative side of

the A battery unless B potentials of more than 135 volts are used. There are two reasons for this practice. The first is that when 135 volts is applied across the filament to the plate of a tube in series with a resistance of 100,000 ohms, a large part of the 135 volts is used to overcome the potential drop across the 100,000

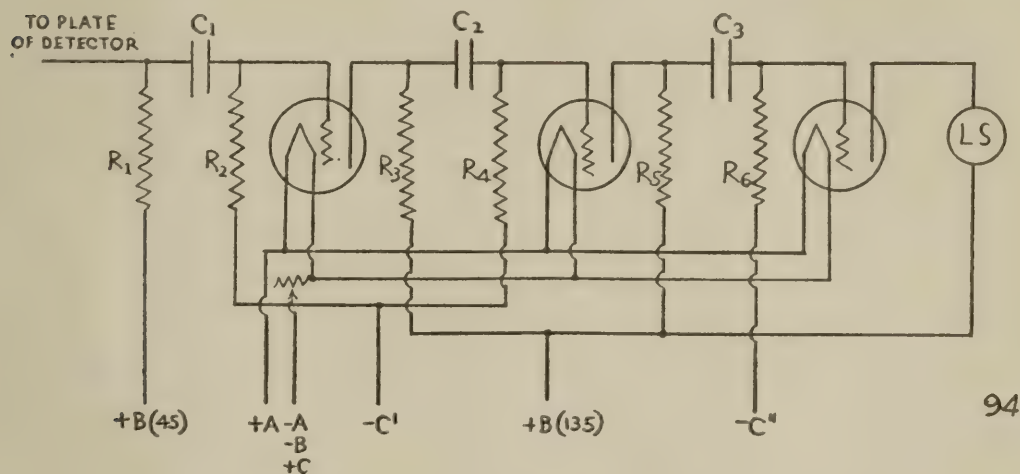


Fig. 94. A Standard Three Stage Resistance Coupled Amplifier

$R_1 = R_3 = R_5 = 100,000 \text{ ohms}$	$R_2 = 1,000,000 \text{ ohms}$
$C_1 = C_2 = C_3 = 0.1 \text{ to } 1.0 \text{ mcf.}$	$R_4 = 500,000 \text{ ohms}$
	$R_6 = 250,000 \text{ ohms}$

ohms. The exact amount left for the tube depends on the condition of the tube. If we recall Ohm's law

$$P. D. = R I$$

we can, by measurement of the plate current with the aid of a milliammeter determine the potential drop across R. A stock tube in the laboratory here showed $I = .001$ amperes, which gives a potential drop over the resistance of 100 volts, leaving only 35 volts available across the tube.

We have also to remember the effect already discussed, namely, the depression of the average value of the grid potential when a condenser is used in the grid lead. It will therefore be more or less evident that the grid will tend to be negative with respect to the average potential of the filament even without the use of a C battery.

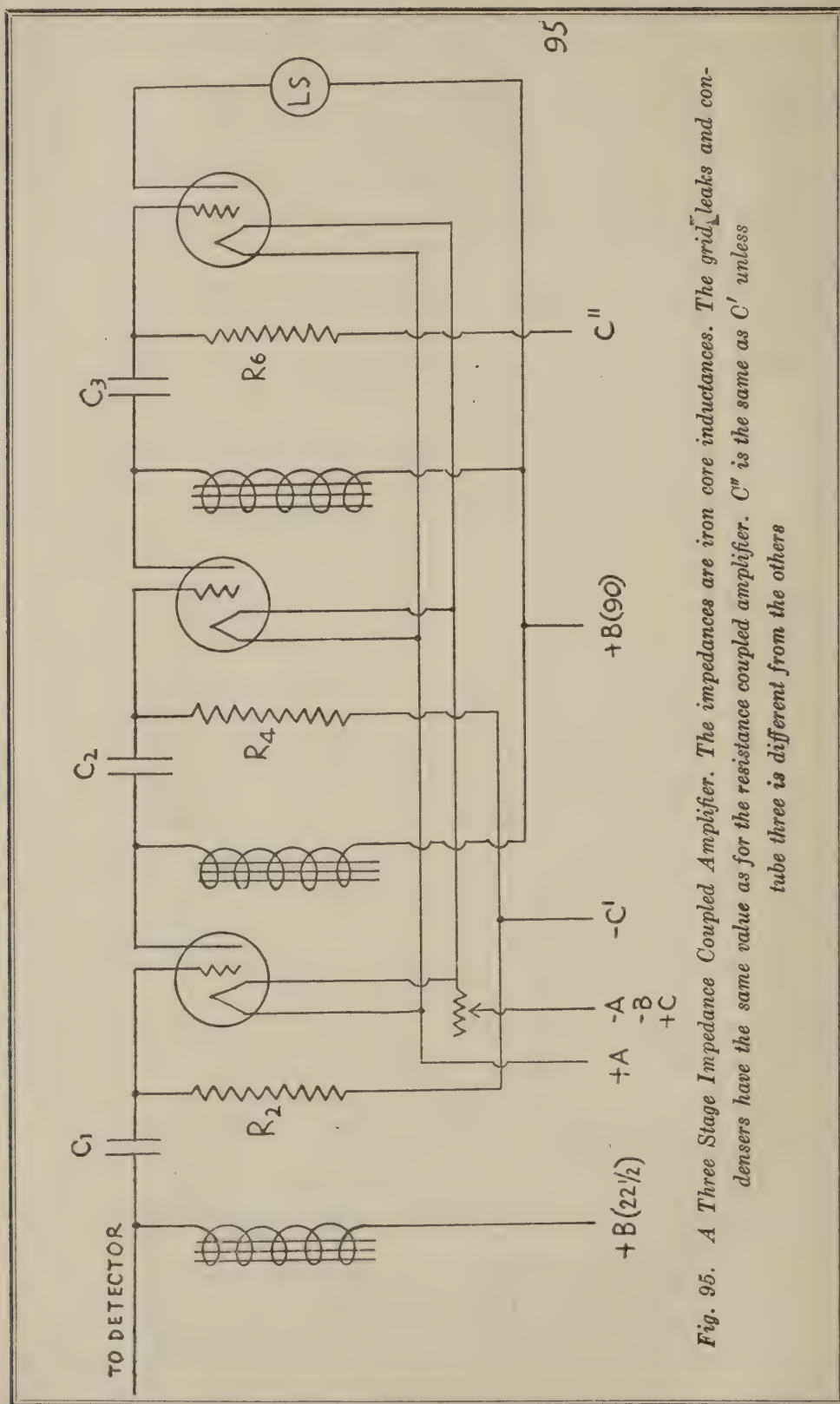


Fig. 95. A Three Stage Impedance Coupled Amplifier. The impedances are iron core inductances. The grid leaks and condensers have the same value as for the resistance coupled amplifier. C'' is the same as C' unless tube three is different from the others

Necessity for Keeping the Grid Negative. It is customary, in all audio amplification, to keep the grid at an average potential sufficiently negative to prevent it from going positive with respect to the filament on the positive half of the incoming cycle of e. m. f. The reason for this is that if the grid goes positive it attracts large quantities of electrons, and since the condenser C_g now behaves as a condenser which is leaky in one direction the shape of the applied e. m. f. is changed and the amplification through the tube is distorted.

Impedance Coupled Amplification. The change from resistance coupled amplification to impedance coupled is a simple one. All that is necessary is that well made inductances be substituted for the plate resistors of Figure 94. Such an amplifier is shown in Figure 95. All of the discussion in the preceding section concerning grid condensers and grid leaks applies with equal force here.

A smaller value of B potential may be used here for it is possible to make high inductances with resistance which is low in comparison to the resistance of the tube itself. So nearly the entire e. m. f. of the B battery is available across the filament to plate of the tube. For this reason also it is always customary to use a C battery with impedance coupled amplification, although the value of the C battery may be somewhat less than that recommended by the tube manufacturer for a given value of plate potential due to the potential depressing effect on the grid when connected through a grid condenser. The voltage amplification per stage of impedance coupled amplification is but little better than for resistance coupling. The outstanding advantage over the resistance coupling is the saving in B batteries, since a considerably smaller e. m. f. is required.

It is to be remembered, however, that when we introduce impedance for resistance, we have another possible source of distortion in addition to those present with resistance. This liability for giving unequal amplification for different audio frequencies lies in the fact that the impedance of any inductance is a function of the frequency. This fact we have already considered

in Chapter V under the discussion of the amplification factor of a tube with resistance or inductance in the plate circuit. We saw there that the amplification factor would be nearly constant over a fairly wide range of frequencies provided the inductance gave a high value of impedance (i. e., $6.28fL$) for the lowest frequencies in the range. In other words, the value of L , the inductance, must be quite large. This necessitates the use of a large number of turns of wire on a fairly good sized core of soft steel. However, when the number of turns of wire is increased the distributed capacity of the windings also increases unless special care is exercised in wrapping the wire. It is hardly practicable to space the turns of wire in a layer, but it is customary to separate the layers with waxed paper or insulating fabric of some kind. The objection to distributed capacity lies largely in the fact that at high frequencies a considerable proportion of the alternating current flows through the capacity instead of through the inductance, hence reducing the amplification of the high frequencies. Another way of looking at the effects of distributed capacity is to consider the fact that to a certain extent the inductance in conjunction with this capacity becomes a partially tuned circuit. The result will be that the amplification about the region of the resonant frequency will be much greater than for frequencies either lower or higher.

The obvious objection to the use of high grade inductances is their increased cost of production as compared to the cost of poor ones. But the quality of the resistance coupled amplifier will not be duplicated unless very high grade inductances are used.

Transformer Coupled Amplifiers. We come now to a special case of impedance in the coupling of amplifier stages. Here the impedance is an inductance which forms the primary winding of a step-up transformer. The secondary may have any number of turns from the same number as the primary up to ten times that number, and hence we see that we may expect a voltage step-up in the transformer itself, whereas in the previous amplifiers discussed, all of the voltage amplification took place in the tubes. A transformer is not an energy amplifier—it is merely a voltage amplifier. Very little alternating current flows in the secondary of the transformer, and so voltage step-up in the ratio of the

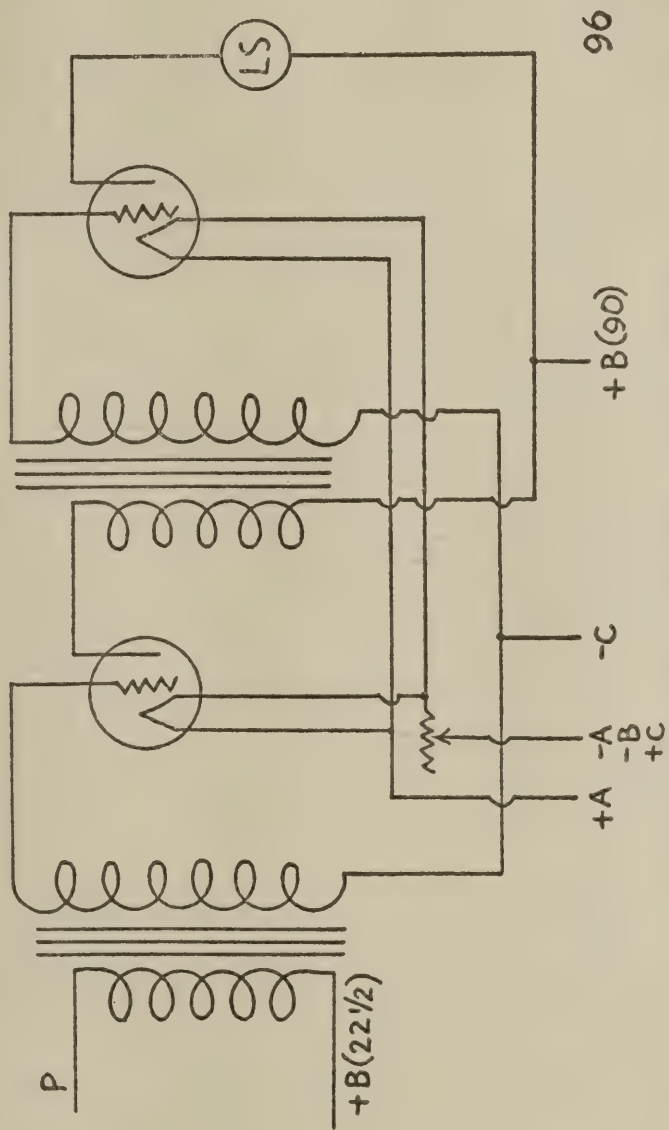


Fig. 96. Two Stage Transformer Coupled Amplifier

number of turns on the secondary to the number on the primary may be obtained.

In Figure 96 we have the wiring diagram of a two stage transformer coupled amplifier. The secondary is connected directly to the grid without the use of a grid condenser, for in this case there is only magnetic coupling between the high potential primary and the secondary. Getting rid of this condenser disposes of one potential source of distortion. The return end of the secondary is connected to the negative terminal of a C battery. As in the case of the simple impedance coupled amplifier very little of the e. m. f. of the B battery is used up across the resistance of the primary and practically all of it is effective across the tube. Further, we do not have the depressing effect on the average potential of the grid in this circuit where there is no grid condenser. Therefore the full amount of C battery recommended by the tube manufacturer for the value of B battery applied should be used. The use of the proper amount of C battery not only improves the quality of the amplification but it also greatly reduces the amount of plate current consumed by the tubes and so increases the life of the B batteries. If transformers of different turn ratio are used, the one with lower ratio should be the first one. The primary of the low turn ratio transformer is usually larger than that of the higher ratio transformer and so matches the impedance of the plate circuit of the detector tube somewhat better.

Transformer coupling is open to all the criticisms mentioned for inductances, and the same suggestions apply for the building of sufficiently high grade transformers. But it is a much more costly process to build a good transformer than a good simple inductance, for if the transformer is to have any appreciable step-up ratio, there must be a great many more turns in its two windings than in the simple inductance. It will be more or less evident then, that a transformer having a turn ratio of two or three is likely to be much better than another transformer costing the same amount but having a turn ratio of ten. The latter transformer may quite likely produce more noise than the former, but we have long since passed the day when the demand of the public was for noise from a loud

speaker. It is of course possible to get fairly good transformers if we are willing to pay for them.

Let us suppose that, in Figure 96, the turn ratio of the transformer is 4 and that the practical amplification factor of the tube is 4. We then see that the voltage amplification per stage is 16 and the amplification of the two stages is 256. This value is somewhat larger than the value obtained for the three stage resistance coupled amplifier of Figure 94. The greater amplification for the number of tubes required has, up to this time at least, made the transformer coupled amplifier more popular than any other. But the fact that there is no transformer yet on the radio market that will give the nearly perfect amplification of the resistance coupling, or even of the simple impedance coupling, has led to the adoption of one or the other of these two types by many people.

Remedies for Oscillating Amplifiers. When poor transformers are used or when good transformers are poorly placed and especially when tubes are old there may occur a tendency for the audio frequency amplifier to oscillate in the audio range. Not only is the persistent note so created very objectionable, but the efficiency of the amplifier is greatly decreased. The customary "cure" for this difficulty is to place a grid leak across the secondary terminals of either or both transformers. The value of the grid leak will have to be determined by trial and may lie anywhere between 100,000 and 2,000,000 ohms. Sometimes a small fixed condenser (about .002 mcf.) will stop the oscillations equally well. Moreover, since such a condenser is likely to be more effective at the high frequencies than the low, it may reduce the amplification of the upper range and so give better balanced amplification of the whole signal. These devices, are, however, in the nature of remedies. Good transformers properly placed do not need such "doctoring."

It is customary to place transformers at right angles to one another unless they are separated by an appreciable distance in order to reduce the possibility of interstage coupling of the audio frequencies. It is especially well not to place either transformer

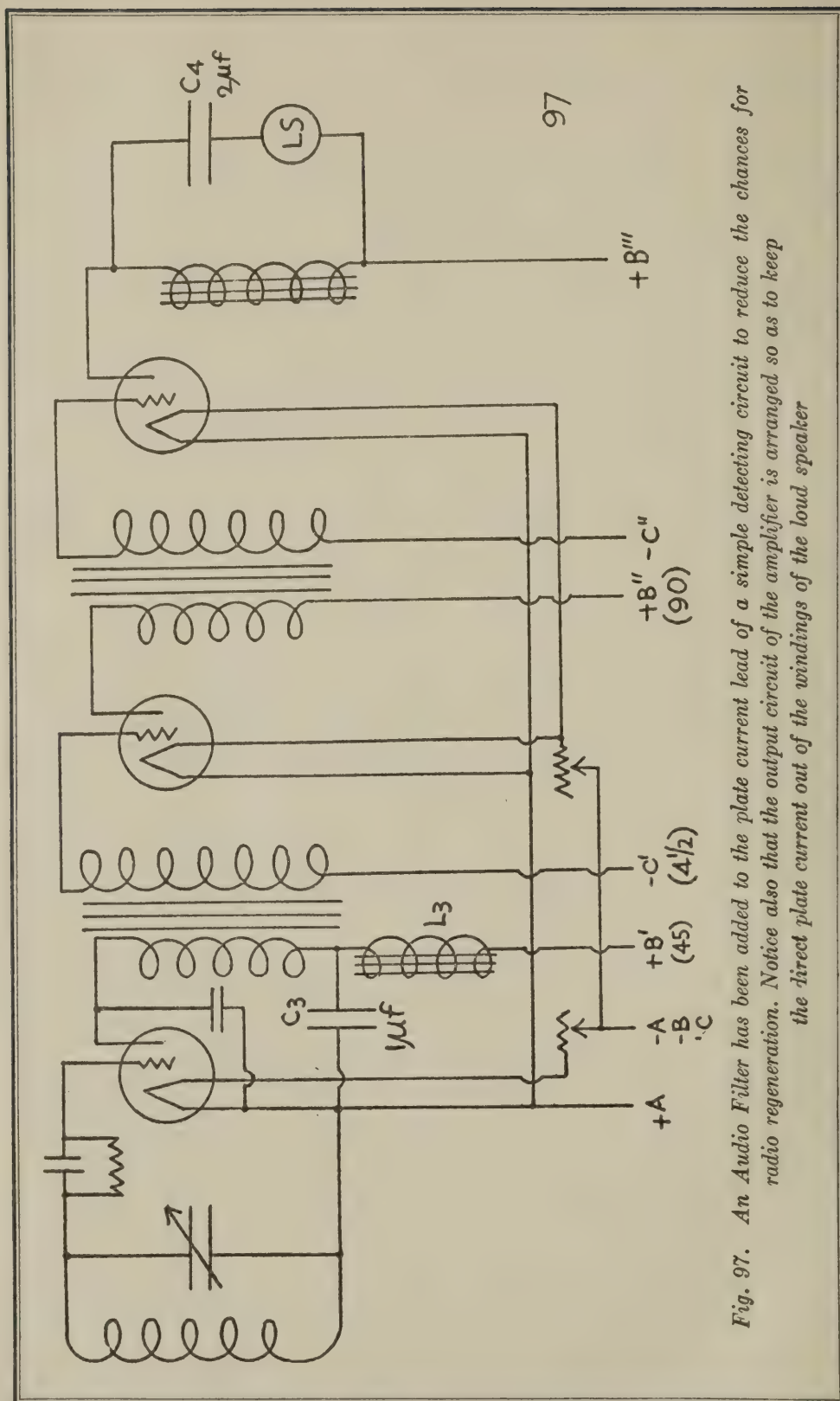


Fig. 97. An Audio Filter has been added to the plate current lead of a simple detecting circuit to reduce the chances for radio regeneration. Notice also that the output circuit of the amplifier is arranged so as to keep the direct plate current out of the windings of the loud speaker

near the input circuit of the detector tube, for otherwise audio regeneration is quite likely to occur. Figure 97 shows a detector tube and two stage transformer coupled amplifier where an iron core inductance L_3 and a bi-pass condenser C_3 (1.0 mcf.) have been introduced in a further attempt to stabilize the audio frequency circuit. This arrangement is due to Mr. H. A. Wheeler. For very large volume a special arrangement of transformer coupled amplification is sometimes used. It is called "Push-pull" amplification and has been described in the first chapter.

Auto-formers. To overcome the low voltage amplification of simple inductance coupling and at the same time keep the excellent quality resulting from that type of amplifier, the auto-former has found its way to the market. Two stages of this amplifier with a simple detector are shown in Figure 98. It is obvious that all of the criticisms of the simpler inductance system plus most of those of the transformer coupling method are applicable to this case. As in all the other instances, it is possible to obtain fairly uniform amplification in this manner; but the writer is inclined to feel that nothing is gained with such a device that could not be had with an equally well made transformer. Then, too, with the transformer, the grid condensers and grid leaks are eliminated.

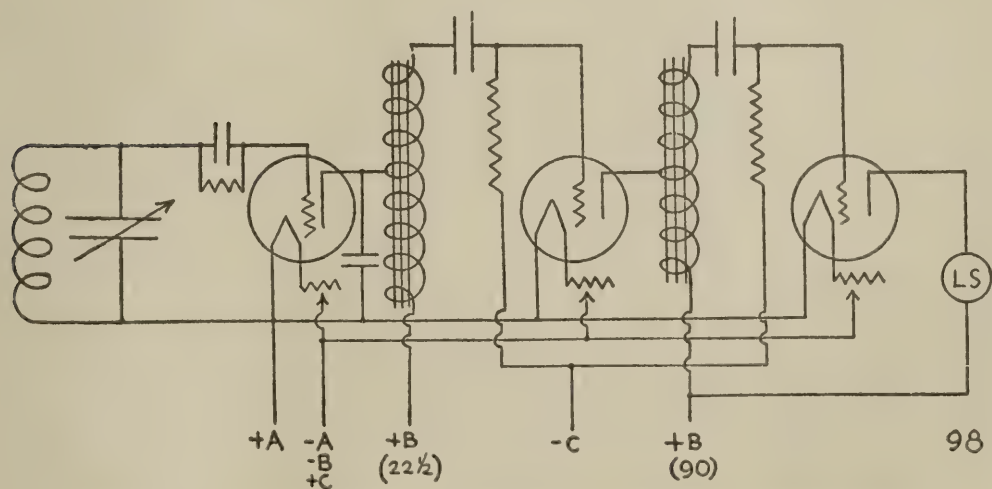


Fig. 98. An "Autoformer" Coupled Audio Amplifier Shown with a Simple Detecting Circuit

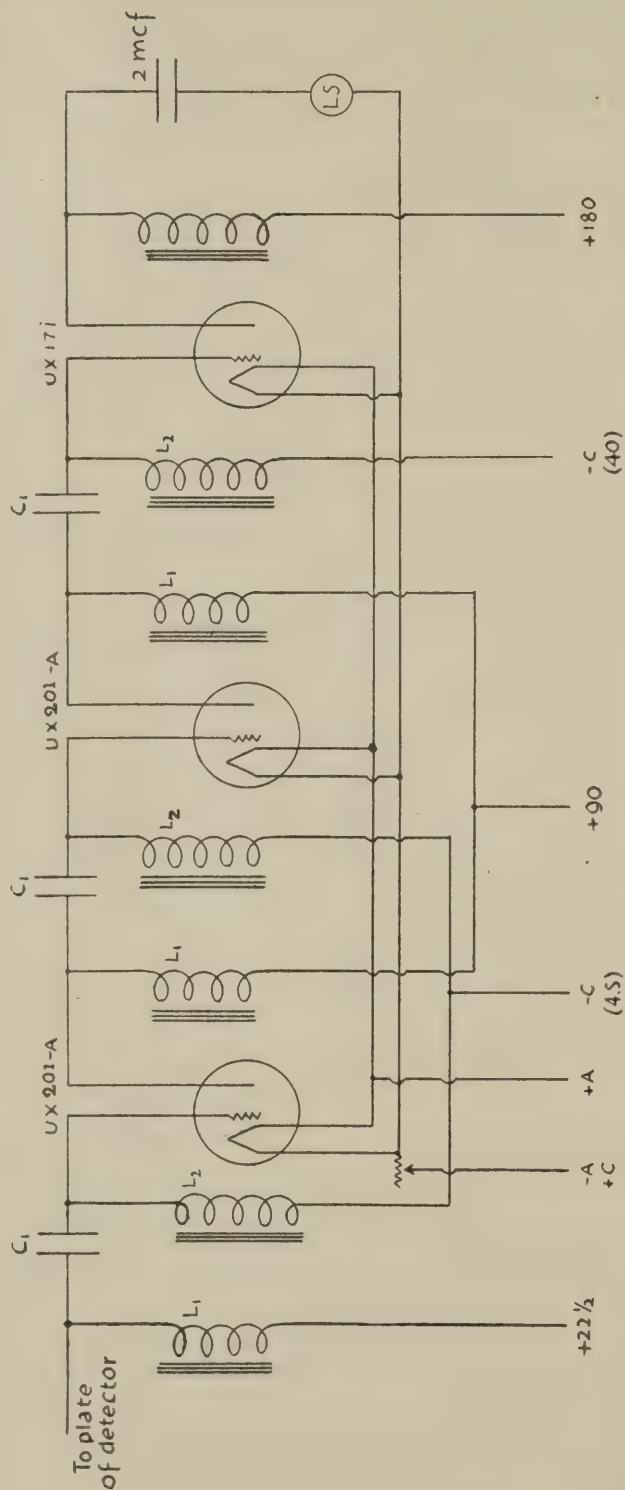


FIG 98-A

Fig. 98-a An Impedance Coupled Amplifier with Large Inductances Instead of Resistors in the Grid Circuits

Double Impedance Amplifier. The late 1926 market has seen a modification of the impedance coupled amplifier which obviates some of the difficulties attendant on the performance of straight impedance and straight resistance coupled amplification. Essentially the only change from the circuit for straight impedance is the substitution of a high inductance for each grid leak. Such an amplifier is shown in Figure 98-a.

High resistances for use as grid leaks have probably been the chief source of trouble in both impedance and resistance coupled amplification. The trouble, in the first place, lies in the lack of dependability of the high resistors on the commercial market both as to their original values and as to the permanence of their values. In the second place, if large coupling condensers (0.1 to 1.0 mcf.) are used, on very loud signals, or on crashes of static, the condensers accumulate such large quantities of electrons that the tubes are blocked for a short interval. This condition can be remedied by using smaller values of resistance in the grid leaks, but this change is accompanied by some reduction in amplification and also by discrimination against the very low frequencies, as may be seen from the related problem illustrated in Figure 93.

With the large inductance substituted for the grid leak we have a copper connection between grid and filament. This removes all uncertainty as to the normal grid potential, prevents blocking, and enables one to use the tube manufacturer's specifications as to size of C battery. For uniform amplification over all frequencies very large inductances should be used both in the plate and the grid leads and the coupling condensers should be large—0.1 to 1.0 mcf.

Mr. H. A. Gates has called the attention of the writer to certain modifications in this type of double impedance coupling. One of these modifications is of interest primarily to the manufacturer and has to do with the design of the inductances so that they can both be wrapped on the same core system. The other particular development has to do with the fact that this amplifier can be made to have selective frequency amplifying characteristics.

Consider any one of the coupling circuits $L_1 C_1 L_2$ of Figure 98-a. Since the lower ends of the coils are connected through non-reactive batteries, the coupling circuit may be thought of as a tuned circuit whose frequency is fixed by the value of inductance of the two coils and the size of the condenser according to our well known relation

$$f = \frac{1}{2\pi\sqrt{LC}}$$

where L is the sum of L_1 and L_2 .

If large inductances such as those now on the market are used for L_1 and L_2 and if a condenser of the size suggested above is adopted this resonant frequency will be below the audible range. But by reducing the size of the condenser the resonant frequency can easily be brought up into the lower part of the audible region. To prevent the circuit from being too sharply resonant so as to produce booming effects on certain tones, the resonant region can be reduced in amplitude at its peak and spread over a greater frequency range by the insertion of resistance any place in the coupling circuit. This resistance may be inserted either between C_1 and L_2 or between C_1 and L_1 .

We have then an amplifier which amplifies the middle and upper audible frequencies quite uniformly and which gives some over-amplification to the lower notes. In general this is desirable both because of discrimination against very low tones by many types of loud speakers and because of the deficiency in low tones in the signal from many broadcasting stations.

Satisfactory arrangements of this type of amplifier can best be made by manufacturers who have facilities for determining the values of the inductances and the correct size of the coupling condensers and resistors. Home-made amplifiers unless built from assembled parts can be made only by cut and try methods. As a suggestion to start on, the experimenter might try coupling condensers of the order of magnitude of from .05 to .005 mcf. and resistors of from 10,000 to 100,000 ohms.

This type seems to be the most interesting and the most promising of the newer types of audio frequency amplifiers. We may

reasonably expect further improvement and modification of audio amplifiers of this kind.

Output Circuits. In Fig. 97 above, the line from the high potential side of the B battery is seen to go to the plate of the last tube by way of an iron core inductance. Connected in parallel with this inductance are the windings of the loud speaker in series with a condenser C_4 . This scheme keeps the direct plate current from flowing through the windings of the loud speaker and hence takes considerable strain from that instrument. At the same time, the audio-frequency currents find the path made of the loud speaker and condenser to be of less impedance than the path through the inductance. To make the scheme effective without distorting the quality or materially reducing the volume it is necessary to use a fairly large inductance, such as the secondary of an audio transformer or preferably a specially made inductance, and to use a large condenser, say 1 or 2 mcf.

Power Tubes. The device just described has come into more general use since set owners have come to realize the advantages of using power tubes for the last stage of audio amplification. The amount of volume that most people expect from a loud speaker involves the use of more energy than an ordinary 201-A tube can supply without introducing distortion. A number of tubes capable of handling larger plate currents have found their way to the market and are being used by the more discriminating listeners. Some people are disappointed with these tubes because they give little if any more volume than the others. Of course if the amount of distortion with the smaller tube is not objectionable to any one listener, there is no point in his investing in larger tubes. Power tubes are for the use of people who wish reasonably good volume with as nearly perfect quality as is possible.

Loud Speaker Impedance and Tube Resistance. Best results in loud speaker operation are obtained when the impedance of the loud speaker windings is roughly equal to the impedance of the plate circuit of the tube. The impedance is a

different function of the frequency for the loud speaker windings than it is for the tube. Hence a perfect match for all the audio frequencies can not be made. Most of the newer loud speakers—especially the cone types—have rather low impedance windings, and the new power tubes with their greatly reduced plate impedance give much better results with these loud speakers than 201-A type tubes.

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**RADIO FREQUENCY
AMPLIFICATION**

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CHAPTER VII

Radio Frequency Amplification

UP TO this point we have considered only circuits in which the detector tube was actuated by e. m. f.s available as the direct consequence of alternating currents flowing in the antenna circuit. It would seem reasonable that the devices used for amplification of audio frequencies might be adapted for use in the amplification of the alternating currents from the antenna circuit before they are fed into a rectifier (detector) circuit. Such a scheme would be highly desirable because of the greater signal currents that the detector would be able to deliver. The amount of audio amplification necessary would then be decreased, and with it some of the objectionable audio noises. For the amplifier ahead of the detector could be tuned to the radio frequency to be received and disturbances of an audio frequency would receive little or no amplification until they had passed the detector.

Resistance Coupled Amplifier. Since the resistance repeating amplifier already described seems to make no differentiations in frequency it would appear possible to put a suitably tuned input and output circuit with this amplifier and so use it ahead of a detector. Such an arrangement is shown in Figure 99. Since only high frequencies are to be handled in this case it is possible to use much smaller coupling condensers than in the audio amplifier. Condensers as small as .0005 or even less would probably be satisfactory, and large grid leaks, say 3,000,000 to 5,000,000 ohms, could be used. There are two principal reasons why this amplifier is not very successful. The first has to do with the fact that it is difficult to make resistors for the plate circuits with low enough distributed capacity and absorption for use at high frequencies. The other reason is that the capacity of the grid to filament offers

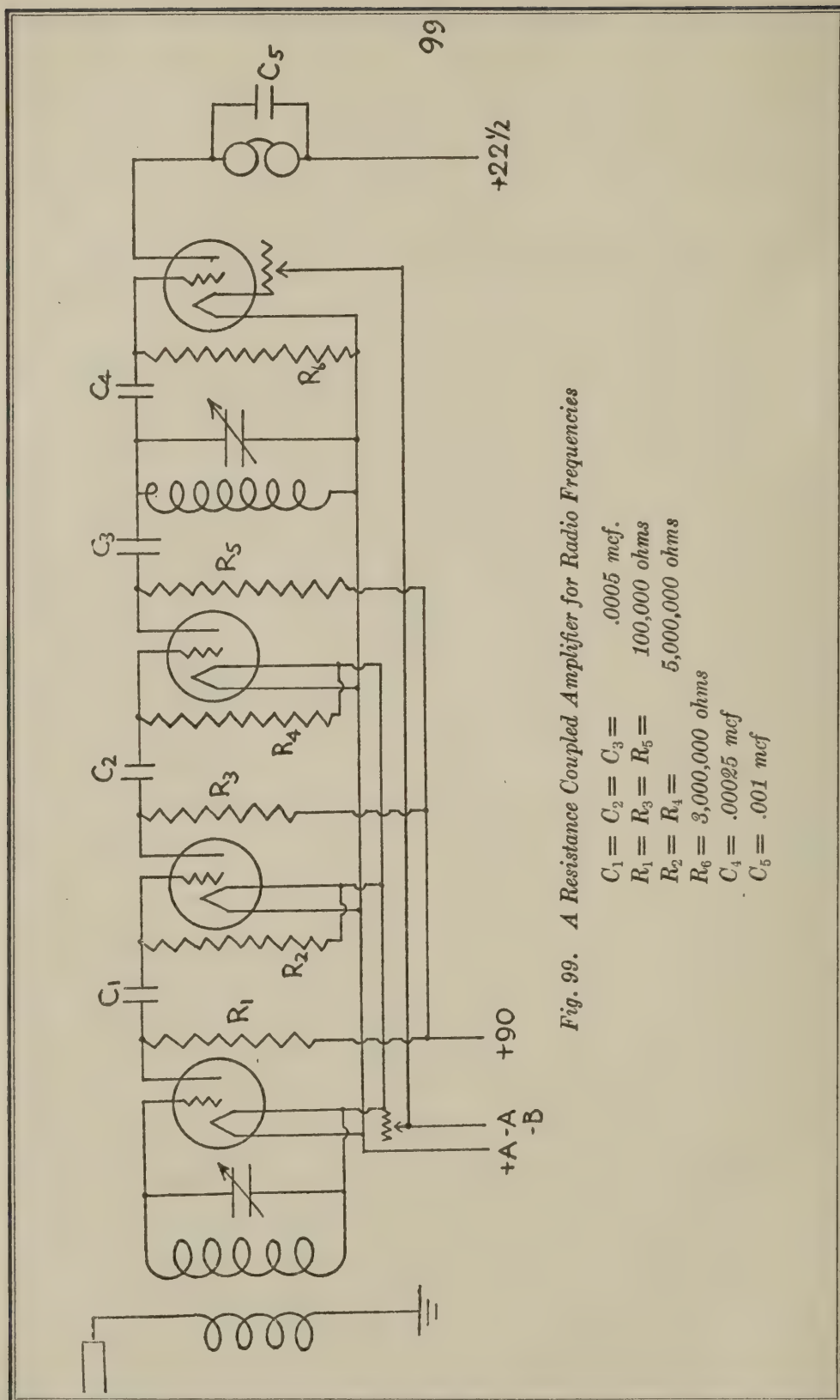


Fig. 99. A Resistance Coupled Amplifier for Radio Frequencies

so low an impedance path to the higher frequencies of the broadcast band as to constitute almost a short circuit around the repeating resistance. At least the potential difference across the grid-filament of the tube would be small. In this connection it is necessary to take into account the fact that the actual capacity of the grid-filament condenser of a tube is different under working conditions with an output resistance or impedance in the plate circuit than it is when the plate circuit is not present. With a large load, such as an inductance or resistance in the plate circuit, and with the tube in operation, the capacity of the grid to filament may be as much as six or seven times the value when the filament is not heated and there is no external plate circuit.

Impedance Coupled Amplifier. As in the case of audio amplification, inductances might be substituted for resistances in the preceding amplifier. They would be subject to all of the difficulties of the resistance coupled amplifier and additional ones due to the effects of the distributed capacity of the windings of the inductances. To make the repeating action good the inductance should be made as large as possible. However, increasing the size of the coil not only increases the inductance but also the distributed capacity, so that a coil which is large enough to be a good repeater will almost certainly have a value of L and C so large as to constitute a tuned circuit within the range of frequencies included among those for which the amplifier is to be used. At and near this resonant frequency the individual stages of amplification may have a high efficiency, but at other frequencies they are likely to be rather poor.

Tuned Impedance. The criticism just pointed out for the ordinary inductance as a connector of stages for radio frequency amplification leads us to consider the possibility of tuned impedances where the tuning is accomplished by means of variable condensers and must be adjusted every time the receiving set is used for a signal of different frequency than the last one to which it was tuned. Such a circuit is shown in Figure 100.

When the circuit $L_2 C_1$ is tuned to the frequency of the incoming signal we find that this circuit offers a very high resistance between the points M and N as might be expected from the dis-

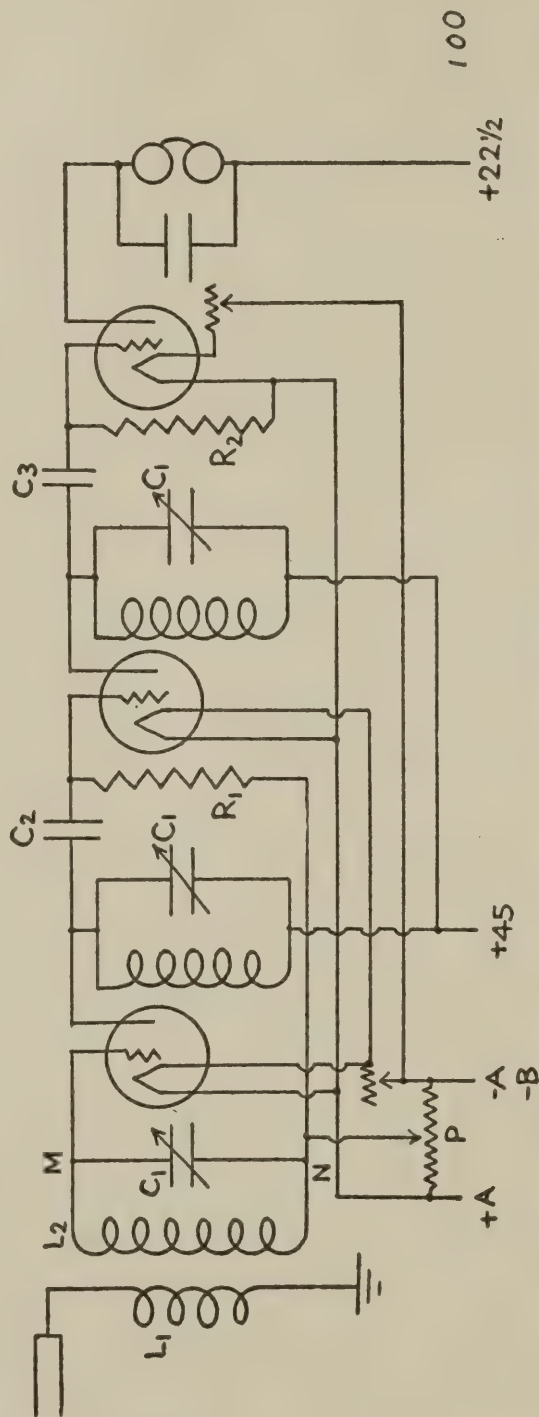


Fig. 100. A Radio Frequency Amplifier Employing Tuned Impedance to Couple the Stages.

$$R_1 = 5,000,000$$

$$R_2 = 3,000,000$$

$$C_2 = C_3 = .00025 \text{ mcf.}$$

P is a potentiometer of about 400 ohms resistance.

cussion of resonant circuits in Chapter IV. Hence the amplification for this frequency may be made to approach the theoretical amplification of the tube. Moreover, the grid to filament capacity of the tube now acts as a part of this tuned circuit as shown in Figure 101 and therefore does not serve to short circuit the inductance

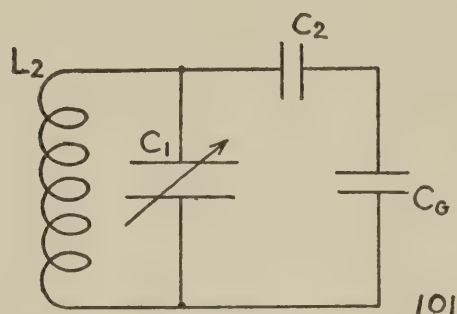


Fig. 101. A Tuned Input Circuit

at this particular frequency. The outstanding difficulty with the circuit is that each stage represents altogether too well the regenerative and oscillating circuit diagrammatically shown in Figure 89 as may be seen from Figure 102. Moreover, the output circuit of one stage of amplification constitutes the input circuit of the next stage, so that the outstanding characteristic of this amplifier is its tendency to oscillate rather than its ability to

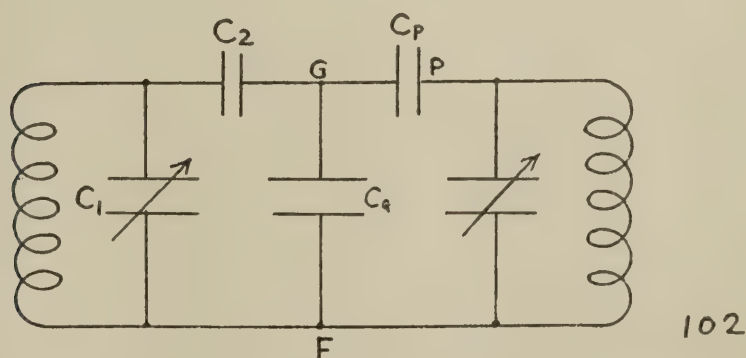


Fig. 102. Diagrammatic representation of the circuits of one stage of tuned impedance amplification showing the capacitive coupling between the various tuned circuits

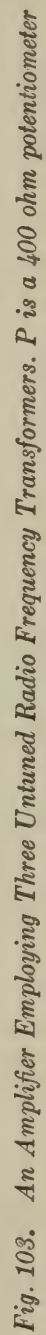


Fig. 103. An Amplifier Employing Three Untuned Radio Frequency Transformers. P is a 400 ohm potentiometer

amplify. Even if it were not for the coupling of circuits through the tube capacities there would be a tendency for coupling between input and output circuits as well as between stages due to the possibility of overlapping of the magnetic fields of so many coils. This latter difficulty can be fairly well taken care of by proper placement of coils provided not more than two stages of the amplifier are used. It can also be controlled by shielding the coils. We shall discuss shielding later on in connection with tuned transformer coupled amplification where many of the problems of the tuned inductance amplifier occur.

Use of the Potentiometer. Figure 100 shows that an attempt to control the oscillations of this amplifier is made by utilizing the fact that the tendency to oscillate varies with the normal grid potential. With a decidedly positive grid there is much less tendency for the tube to oscillate than when the grid is negative. Of course the amplification for negative grid is not only greater, but also more nearly distortionless, but these things must be sacrificed to gain stability. Actually the volume does not suffer by this method because the normal grid potential can be so adjusted as to keep the set just under the oscillation point but in a state of regeneration. Theoretically the grid potential of each tube should be separately controlled by means of a potentiometer for each tube. Actually this would increase the number of tuning controls to an absurdly large number, and hence the less efficient, but more practical scheme of using only one potentiometer as shown in Figure 100 is ordinarily used. Tuned impedance has occasionally been employed in sets designed for broadcast reception, but since it offers most of the difficulties and not all of the advantages of tuned transformer coupled amplification it has usually been discarded in favor of the latter.

Transformer Coupled Amplifier. Fig. 103 shows a transformer coupled amplifier where the transformers are designed to handle radio frequencies and where stabilization is gained through the use of a potentiometer to control the normal grid potential. It is customary to build radio frequency transformers with-

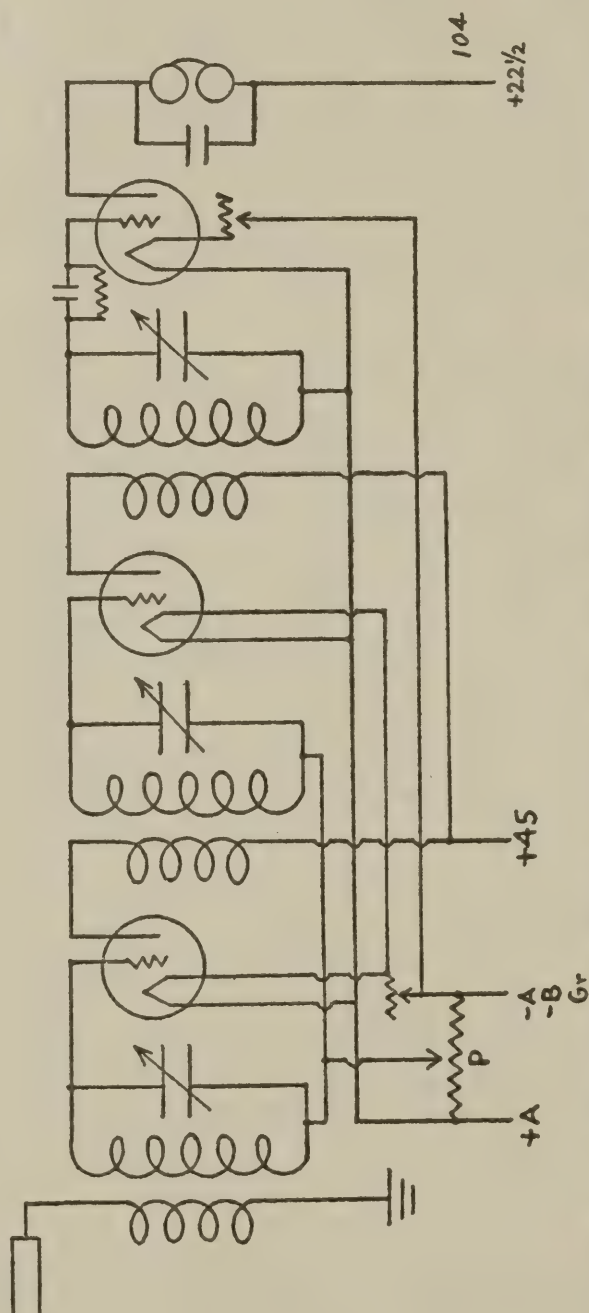


Fig. 104. A radio frequency amplifier employing three tuned transformers. Stabilization is brought about by means of the potentiometer, P, or the rheostat that controls the filaments of the first two tubes.

out iron cores to avoid eddy current and hysteresis losses in the cores. Sometimes, however, they are built with either powdered or finely divided iron as a core. Sometimes the powdered iron is put into melted sealing wax. The wax is then poured into the coil of wire and permitted to harden there. Regardless of the care in the construction of these transformers there is always a great deal of magnetic leakage, so that the transformer does not approach ideal conditions nearly enough to enable one to predict its voltage step-up in terms of the turn ratio of the windings. Also the grid to filament capacity of the tube in operation acts as a shunt circuit across the secondary of the transformer for most frequencies somewhat as it did in the case of resistance coupled amplification for all radio frequencies. Of course, if the secondary coil with its distributed capacity in connection with the tube capacity has a resonance point in the region of frequencies to be received, reception may be fairly good for those frequencies. It is necessary to consider the distributed capacity of both the primaries and the secondaries, and if we consider a single stage of the amplifier with both its output and input circuits, it is at once apparent that we have a possible oscillating circuit. Nevertheless, fair results have sometimes been obtained by permitting such an amplifier to regenerate moderately by carefully adjusting the potentiometer.

Tuned Radio Frequency Transformers. We come logically now to the type of amplifier where stage coupling is effected through transformers the secondaries of which are intentionally tuned. Figure 104 shows such an amplifier and again we see that stabilization has been effected with the aid of the potentiometer. It may not be at once apparent that this amplifier has any inherent tendencies to oscillate, for it is well known that in almost all of these tuned transformers the primary coil is made with many fewer turns than the secondary. Moreover, the secondary has a fairly large tuning condenser shunted across it, whereas the primary has none. Nevertheless, due to the fact that this primary is coupled to another tuned secondary the entire circuit will behave very much like the regenerative receiver of Chapter VI, Figure 85. That this is true will be more apparent after we have gone further into the effects of one circuit on

another when they are coupled either magnetically or electrostatically.

Much of the present chapter will be devoted to better methods of securing stabilization than the potentiometer method already given, but we shall first attempt to discover the reasons why we may expect greater amplification with tuned than with untuned transformers. If we neglect the one way conductance or leakage

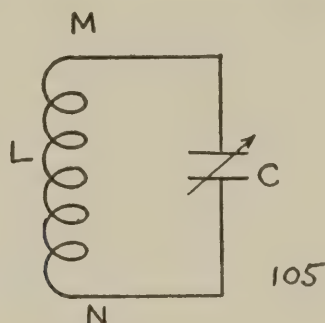


Fig. 105. The e. m. f. developed across the inductance in a tuned circuit is equal to $6.28 f L I$ where L is the inductance, I the current and f the frequency

of the filament to grid condenser and treat it as a perfect condenser in parallel with the tuning condenser we may represent the tuned secondary input circuit as a simple tuned circuit. For maximum amplification it is desirable to impress the greatest possible e. m. f. across the grid to filament. Now the potential difference across the coil L in Figure 105 will be as we have previously seen $6.28 f L I$ where f is the frequency, L the inductance and I the current. For a given frequency it is obvious that the two possible ways of increasing this potential difference are to increase the inductance or to increase the current flowing.

Size of Secondary Inductance. If we increase the inductance we must decrease the capacity C in order that the coil condenser circuit may tune to the same frequency as before. Decreasing the tuning capacity increases the tendency of the set to oscillate, as will be pointed out again in a discussion on capacity coupling. Moreover, if the maximum capacity be made very small in order to permit of the use of a large inductance it will not be possible to tune down to the lowest wave-length (highest frequency) stations. For the minimum

capacity of the condenser added to the distributed capacity of the coil will give a value of capacity which is too large for use with the large inductance for tuning to the high frequency signals.

There is another difficulty with making the inductance large. When the size of the coil is increased, i. e., the number of turns made greater, we use more wire and hence increase the resistance of the coil. In a tuned circuit, the reactance of the coil and condenser cancel one another and the amount of current that flows for a given e. m. f. between any two points of the circuit is dependant upon the conductance, i. e., the reciprocal of the resistance of the circuit. So if we increase the resistance of the coil while we increase its inductance, we offset to some extent the gain resulting from the increased inductance. To overcome this objection we may increase the size of the wire and all the dimensions of the coil, thus reducing the other difficulty, namely, the increased distributed capacity of the coil, at the same time that we are attempting to keep the resistance from becoming too great. But increasing the dimensions of the coil increases the tendency of the magnetic fields of the coils in one stage to overlap the fields of coils in other stages; and so the stability of the entire amplifier is reduced. It must be evident that the problem is a complicated one where both advantages and disadvantages attend every change.

Perhaps the most commonly used size of inductance is one which, when used with a .0005 mcf. condenser, will just tune to a 550 meter (545 Kilocycle) station at the maximum setting of the condenser. If a set is well balanced, a smaller condenser may be used, and many sets now on the market employ a .00035 mcf. condenser and the correspondingly larger inductance. This size of inductance seems to offer the best compromise between the advantages and disadvantages of the larger inductances. We shall discuss the sizes of these coils and their general construction further after some of the more typical tuned radio frequency circuits have been described.

Relative Sizes of Primary and Secondary. We have already touched upon one requisite for producing a large current in the tuned circuit, namely, keeping the resistance

of the circuit low. Two other considerations which are really closely related to one another are the size of the primary and the degree of coupling between the primary and secondary. This problem brings us face to face with the problem of tuned coupled circuits, a field of study too long and involved for this text. We shall, however, note a few of the results and consequences of this study. First, a transformer of this type does not sufficiently resemble the ideal transformers of power engineering to permit the use of the customary rules for transformers. In particular, the e. m. f. induced across the secondary as compared to that across the primary is not a simple function of the ratio of the turns. Since the number of turns of the secondary is pretty much established by the conditions already discussed, the only way to increase the turn ratio is to use a small number of turns in the primary. Actual experiment shows that reducing the primary to much less than one-third the number of turns does not increase the e. m. f. across the secondary. In fact a reduction of the primary very far below this value actually results in a *decrease* of the e. m. f. developed in the secondary circuit. Professor Hazeltine, the inventor of the neutrodyne, has shown that under certain standard conditions best results are obtained when the turn ratio of secondary to primary is approximately 2.8. However, when so large a primary is used we again find that the set tends to become unstable, so that in the interest of reducing the liability of the set to oscillate we find it necessary to use a somewhat smaller primary than the one which develops the largest e. m. f. in the secondary. It is to be remembered, however, that if a set is produced with a very small primary, it is extremely likely that the small primary has been used to offset the weakness of the method used to prevent oscillations.

Coupling of Windings of a Tuned Transformer.

Experiment also confirms the theoretical predictions of the study of coupled tuned circuits that maximum current flows in the secondary for a coupling of primary and secondary that is not too tight. In other words, a one to one coupling does not result in maximum current in the secondary circuit. The exact value of coupling for maximum current in the secondary is, among other things, a function of the resistance of the primary and secondary circuits

and also a function of the frequency. It follows then that to obtain maximum efficiency from a tuned radio frequency transformer one should vary the coupling as he tunes from stations of high to those of low frequency or vice-versa. Such a procedure would complicate the tuning, and the gain in efficiency would not warrant its use. The value of coupling must then be a compromise, and it will probably be the one best adapted to the middle region of the broadcast frequencies. This coupling will be too close for the high frequencies and will tend to make the set regenerate or perhaps even oscillate on these frequencies unless it is well stabilized. Meantime the coupling will be too loose for the low frequencies (long wavelengths) and signals from such stations will not come in quite as well as the others.

Coefficient of Coupling. The degree of coupling between two circuits is defined as the mutual reactance divided by the square root of the product of the reactances of the same kind in each circuit. For an inductively coupled circuit we would have

$$K = \frac{6.28 M}{\sqrt{6.28 L_1 \times 6.28 L_2}} = \frac{M}{\sqrt{L_1 L_2}}$$

where M is the inductance resulting in either coil as a result of the presence of the other. L_1 is all the inductance of one circuit and L_2 all the inductance of the second circuit. M is called the mutual inductance. It is to be noticed that where the coupling is magnetic, only the inductances appear in the definition of degree of coupling. Had the coupling been capacitive, as it is in the case of the input and output circuits of a tube coupled by the capacity of the tube elements, only capacities would appear in the relation thus

$$K = \frac{\frac{I}{6.28 C_m}}{\sqrt{\frac{I}{6.28 C'} \times \frac{I}{6.28 C''}}} = \frac{\sqrt{C' \times C''}}{C_m}$$

where C_m is the coupling capacity, C' all the capacity in one circuit and C'' all the capacity in the other.

Many manufacturers who use small primaries place them very close to the secondaries, even winding them on top of the secondaries in some cases to increase the mutual inductance and hence effect a greater transfer of energy from the primary to the secondary. This procedure has, as we might by this time have suspected, a bad feature. It tends to reduce the selectivity of the set. This tendency is not serious in a set employing three or four stages of tuned radio frequency, for here the selectivity per stage does not have to be extremely good. But in a two stage amplifier, selectivity is likely to be a limit on the amount of mutual inductance whether it be gained by using a large primary or by placing a small primary extremely close to the secondary.

Undesirable Electrostatic Coupling. There is another objection to placing the primary too close to the secondary and this is due to the fact that when the two coils are very close electrostatic coupling between the coils must take place. Now the e. m. f.s developed in the secondary by electrostatic coupling with the primary will, in general, be out of phase with the e. m. f.s developed through the magnetic coupling. So we have two counter-acting effects, and the outcome of the situation is a reduction in efficiency and a lowering of the overall amplification of the amplifier.

An attempt has been made to avoid this undesirable capacity coupling by Messrs. Browning and Drake who have designed a radio frequency transformer in which the primary is bunched closely together and placed near one end of and inside of the secondary. A reference to this transformer will be found at the end of Chapter IX.

Action of the Filament-Grid Capacity. The precise details of transformer construction are seen to be more or less in the nature of compromises between various effects. Nevertheless, it is observed that when a circuit is tuned to the frequency of signal desired, fairly large currents can be made to flow in the circuit even though the applied e. m. f. may be quite small. Furthermore, these currents can be made to produce

fairly large e. m. f.s across the grid to filament of a tube. For this frequency to which the circuit is tuned the capacity C_g behaves as a part of the tuned circuit and does not act to short circuit the secondary of the transformer. For these reasons it would appear highly desirable to utilize tuned transformers as the coupling devices in a radio frequency amplifier. The only drawback then seems to be the inherent tendency of the circuit to oscillate and the number of tuning controls.

Undesirable Coupling Through Tubes. In Fig. 106 is presented diagrammatically the input and output circuit of a stage of this tuned amplifier together with the input circuit of the following stage. Now the coupling between the output and the following input, that is, the coupling between the primary and second-

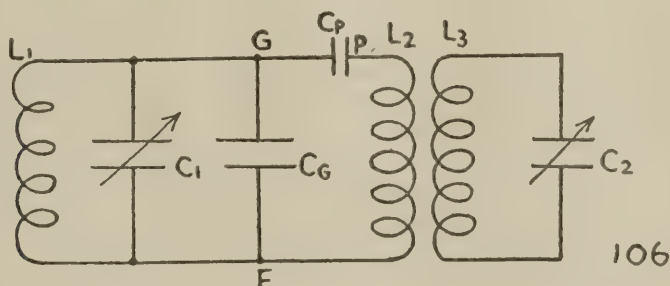


Fig. 106. Schematic Drawing of a Stage of a Tuned Radio Frequency Amplifier with the Input of the Next Stage

ary of the transformer is highly desirable for the successful operation of the transformer. Therefore we turn our attention to the coupling in the tube to see if anything can be done to nullify the effects of that coupling and so reduce the probability not only of single stage, but also of interstage, oscillations. For the sake of ease in analysis we might take the simplified diagram of Fig. 107 instead of that of Figure 106. The coefficient of coupling for this case has been shown to be

$$K = \frac{C_p}{\sqrt{(C_1 + C_g + C_p)(C_2 + C_p)}}$$

From this result it is apparent that if C_p were made very small or if C_1 and C_2 were made very large the tendency to oscillate would be greatly reduced. We have already seen, however, that increasing the size of C_1 and C_2 is undesirable from the point of view of impressing the maximum e. m. f.s on the grid to filament

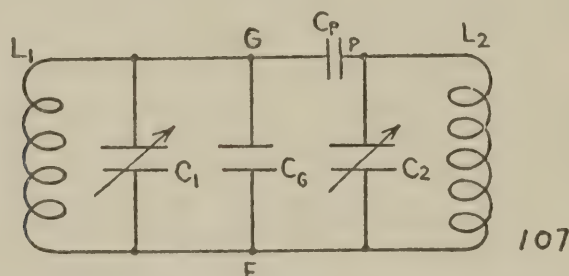


Fig. 107. *Simplified Form of the Circuits in a Stage of a Tuned Radio Frequency Amplifier*

of the tubes. Nevertheless a very ingenious scheme for utilizing the effects of large capacity in these circuits has been worked out by C. L. Farrand and will be found in the list of references at the end of this chapter. We have remaining the possibility of making tubes with smaller values of C_p , but it does not seem likely that tubes can be produced with this capacity sufficiently small to make it negligible. Meantime we must work with tubes now on the market.

Methods of Stabilizing Tuned Circuits. If we neglect the potentiometer method of stabilization and also the method of Farrand just referred to, we may roughly divide all other methods into two classes, first, methods which, by means of auxiliary circuits, supply e. m. f.s to the grid which are equal and just 180° out of phase with the e. m. f.s normally produced in the grid as a result of the high frequency component of the plate current flowing across the condenser C_p ; and second, methods which increase the energy losses of the grid circuit to such an extent that the energy fed back through the tube capacity is not sufficient to supply all of these losses.

The first of these types was brought to the attention of the public in the justly famous circuit of Professor Hazeltine under the patented name of "Neutrodyne." There are now several other methods of "neutralizing" the effects of the capacity C_p which compare favorably with that of Hazeltine. Practically all of these methods, including Hazeltine's, are more or less clever applications of the alternating current bridge already introduced as a device for measuring inductances and capacities. The bridge as introduced for measuring purposes ordinarily has two arms made of either inductances or capacities and the other two (often called the ratio arms) made of non-reactive resistances. However, it is possible to make the bridge with inductance in all four branches, or capacity in all four branches, or inductance in two adjacent branches and capacity in the other two.

The Neutrodyne. The Hazeltine method, like a majority of the others, uses the form of bridge containing two arms made of inductances and two of capacity. All of these bridge methods should give uniform neutralization throughout the range of frequencies for which the receiver is to be used, for the balance of

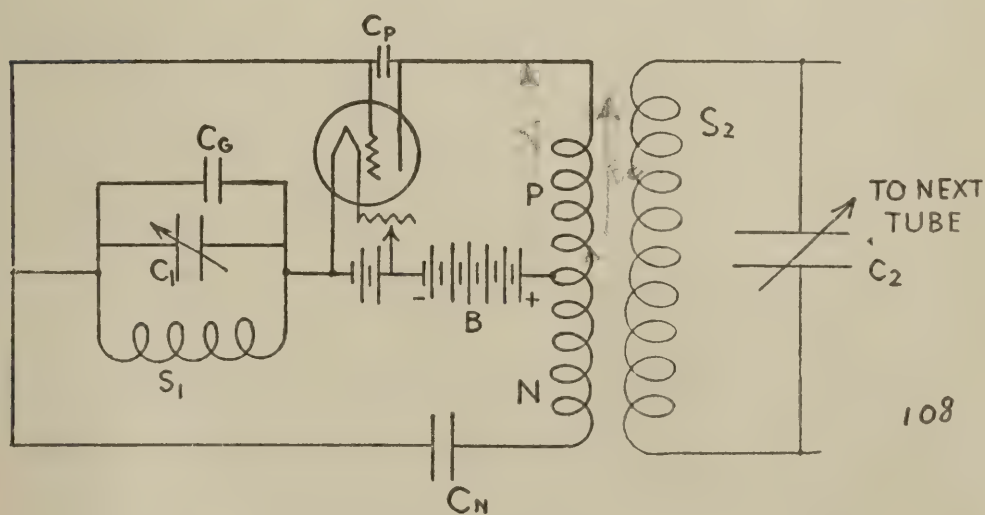


Fig. 108. One Stage of a Neutrodyne Receiver showing (in light lines) the Tuned Input of the next Stage

the bridge is good for any frequency. Actually the bridges are never perfect enough to make the balance uniformly good over any very large frequency range due to the fact that the many other parts of the receiving circuit are not without influence on the bridge. However, it is possible to make the circuit well enough

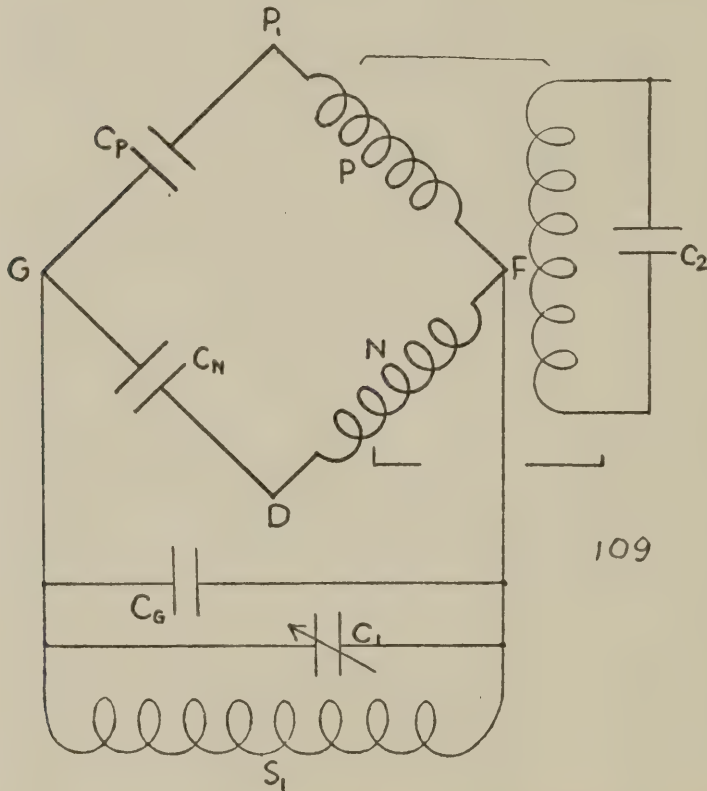


Fig. 109. The Neutrodyne Circuit shown as an Alternating Current Bridge

to give sufficient neutralization throughout the broadcast range.

To make the principle of the neutrodyne clear two diagrams have been made, the first, Figure 108, showing the tube and batteries as well as the inductances and capacities involved. The second diagram, Figure 109, shows the same circuit in the form of the bridge and with all of the non-essentials, such as batteries, omitted. In the first of these diagrams the tube capacities have been indicated externally to the tube.

The circuit does not function as a simple alternating current bridge for the reason that the coils P and N are coupled the one to the other. That is to say, there is mutual inductance between the two arms of the bridge and this mutual inductance must be added to both P and N. The presence of the tuned circuit S_2C_2 will also affect the value of P and N but will affect each equally if the coils P and N are equal the one to the other and are closely coupled.

Now if the bridge is properly balanced, that is, if

$$\frac{C_n}{C_p} = \frac{P}{N}$$

where P and N include the mutual inductance of one another and also the effect of the presence of the tuned circuit S_2C_2 , no e. m. f.s will be developed between the points D and P_1 due to the currents flowing through GP_1F and GDF due to e. m. f.s applied between the points G and F by the tuned input circuit. Consequently if P and N have their turns wrapped in the relative direction indicated in the drawings, the effects of the currents in the two coils will be opposed to one another and no e. m. f.s will be induced in the coil S_2 .

On the other hand, when currents flow in the coil S_2 e. m. f.s will be induced over the coils P and N in such a manner as to be equivalent to the application of an e. m. f. between the points P_1 and D; but if the bridge is balanced the currents resulting from these e. m. f.s can not produce potential differences between the points G and F. In other words, the circuits of one stage of amplification are independent of those in the next stage so far as the effects of tube capacity coupling are concerned. This discussion has been concerned with the effects of tube capacities, not with the alternating component of the plate current resulting from the action of the varying grid potential on the plate current, except in so far as this current gives rise to the objectionable e. m. f.s whose effects are to be restricted by the "bridge."

Adjusting the Neutrodyne Bridge. The fact that the circuits of successive tubes are independent except for the plate currents of the tubes is utilized in adjusting the bridge. The variable arm is C_n . If P and N are equal this condenser must have a capacity equal to C_p . The simplest manner of adjusting the value of C_n is to tune the entire receiver to some strong local signal. (See Figure 111). The set will probably oscillate violently now. Then cut off the filament current in the first tube either with a rheostat, or if a common rheostat is used as shown in Figure 111, by placing a piece of paper over one of the filament prongs of the tube. Re-adjust all of the tuning condensers and you should be able to hear the local signal, since the capacity of the first tube will pass it on to the rest of the set. The capacity of C_n is now varied until no signal comes through. Then the current is turned through this tube's filament and the next tube is turned out and adjustment made on its circuits in the same fashion.

Construction of the Transformer Coils. The best practice seems to be to wind the two coils P and N together, that is, to take two pieces of wire and wrap both at the same time on to a piece of fibre tubing. The first end of one coil is joined to the last end of the other in the manner indicated in Figure 110. Since now the coils P and N are equal it follows that the neutralizing condenser C_n must have the same capacity as the effective value of C_p . Wrapping the two coils together in this fashion gives them practically a one to one coupling. This effect is desirable in order that the effect of the secondary circuit to which P is coupled may have the same effect on both coils, and also to prevent the bridge from behaving as though one of the capacity arms contained part of the inductance of P. These effects are discussed at length in an article in the *Proceedings of The Institute of Radio Engineers* referred to at the end of this chapter. Figure 111 shows two neutralized stages of amplification and a detector.

Another common practice is to wind a continuous coil as is indicated in the circuit of Figure 108. The B battery tap is then taken from the middle of this coil. This method is open to the

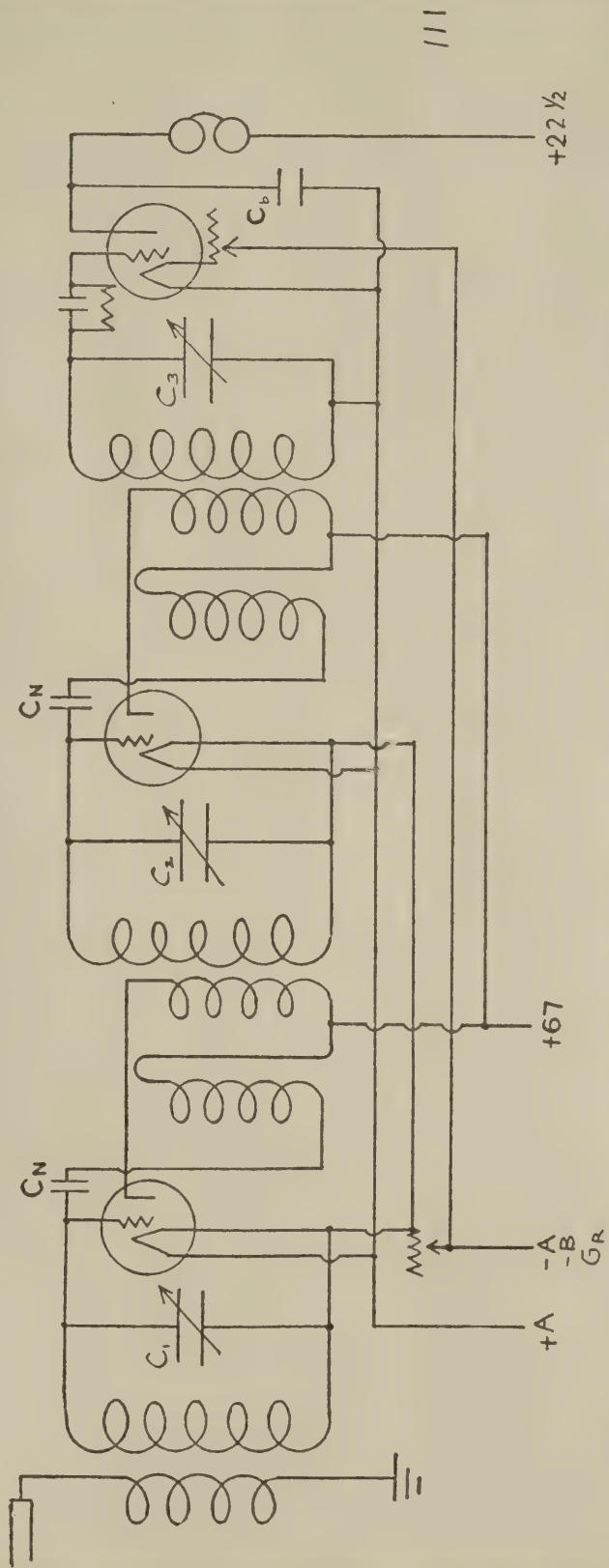


Fig. 111. A Two Stage Neutralized Tuned Radio Frequency Amplifier with Detector

No. 28 or even 30 or 32. It is better not to use too small wire, however, since the resistance of this circuit adds to the effective resistance of the circuit coupled to it. Larger wire is used on the secondary, there being little difference in the efficiency of the secondary for sizes lying between 18 and 26 gauge. The wire on the secondary is usually spaced somewhat more than occurs naturally from the thickness of the insulation. Sometimes it is space wound by machine and sometimes the tubing is threaded and the wire wrapped in the groove. Where the wire is thus separated, enameled wire may be used since the enamel will not increase the distributed capacity much when the turns are not very close together.

Another Method for Hazeltine Neutralization.

Practically all of the early neutrodynes and many of the present models employ a different method of obtaining potentials of the right magnitude and phase to apply to the grid of the tube for neutralization. Instead of having a separate coil N, a part of the secondary may be used. These sets have come into very popular use and Figure 112 shows the standard circuit diagram. Two stages of tuned radio frequency with neutralization from the secondaries is shown. The detector is non-regenerative, and the audio amplification is by transformer coupling.

Placement of Coils. With so many coils it is necessary to take precautions to prevent the exchange of energy through magnetic coupling as well as through tube capacities. Overlapping of the magnetic fields of the coils may be prevented either by proper placing of the coils or by shielding them. If three coils are placed mutually at right angles to one another and on the same line of centers there will be no magnetic coupling between them. Professor Hazeltine also developed a scheme for placing any number of coils so that no coupling would exist between them. His method is to place all of the coils on a common line of centers and to place each coil so that the angle between its axis and the line joining all the coils will be 54.7° . The best angle is sometimes one or two degrees different from this value due to the effects of connecting wires. In any case, the

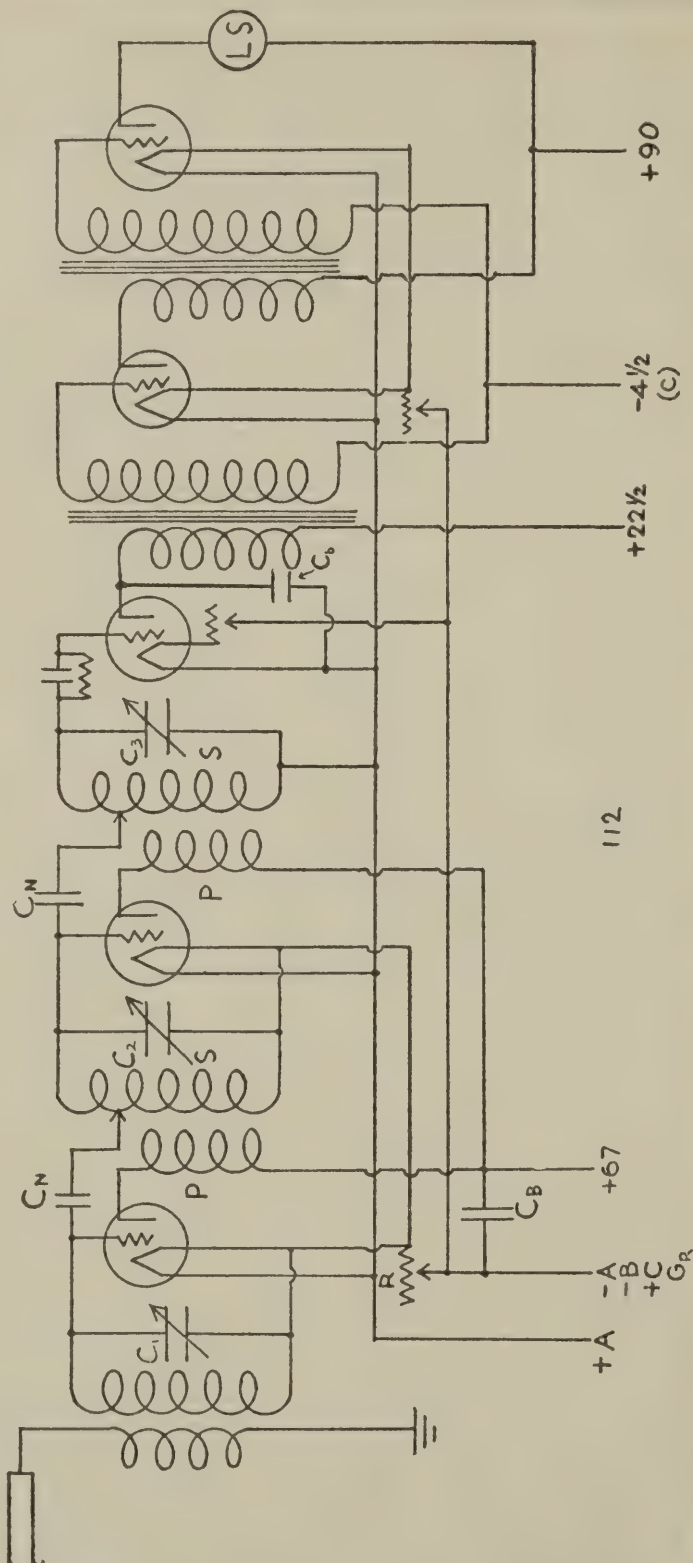


Fig 112. A Standard 5-Tube Neutrodyne where each Neutralizing Condenser is attached to the following Secondary instead of to a Special Coil. It is very necessary to keep the relative directions of winding on the coils P and S as indicated here.
Volume is controlled with the rheostat R. $C_b = .1$ mcf.

coils should be mounted so that no metal will be close to the open ends of the coils, otherwise eddy currents will be set up in the metal by magnetic induction, and this energy to maintain the eddy currents will be supplied at the expense of the current in the coil.

Shielding. When shielding is employed there is seldom any attempt made to place the coils at right angles or according to Professor Hazeltine's arrangement. They are ordinarily placed on a common line of centers and with their axes all parallel. The shielding usually consists of a complete box around each set of coils. The box is made of thin brass or copper, of 30 to 40 mils in thickness. The shields should be large enough so that the metal is at least two inches from the ends of the coils. If the coils are of large diameter, this distance should be greater. Otherwise the losses introduced into the coil system become large enough to be objectionable. Copper shielding acts in a rather indirect way as a magnetic shield in this particular case. When alternating currents flow in the coil the changing magnetic field sets up feeble eddy currents in the copper shield. These currents have magnetic fields of their own which are oppositely directed and nearly equal to those fields reaching the shield from the current of the coil. It follows then that the magnetic fields outside of the shield neutralize one another.

The efficiency of this type of shielding does not increase much with increasing thickness of copper so that little would be gained by using 80 mil copper instead of 40 mil. On the other hand, two thicknesses of copper insulated from one another would be more effective than a single shield. All shielding is, of course, grounded at some point.

While shielding is used primarily to prevent the overlapping of alternating magnetic fields in a receiver, especially in sets employing three or more stages of tuned radio frequency amplification, it serves another useful purpose in shielding the coils from external electro-magnetic influence. One of the causes for interference by local stations is that the coils of the receiver can pick up sufficient energy to bring the signal through even when the set is tuned to some other wave-length. A signal so picked up by any but the first coil is subject to less selective action on the

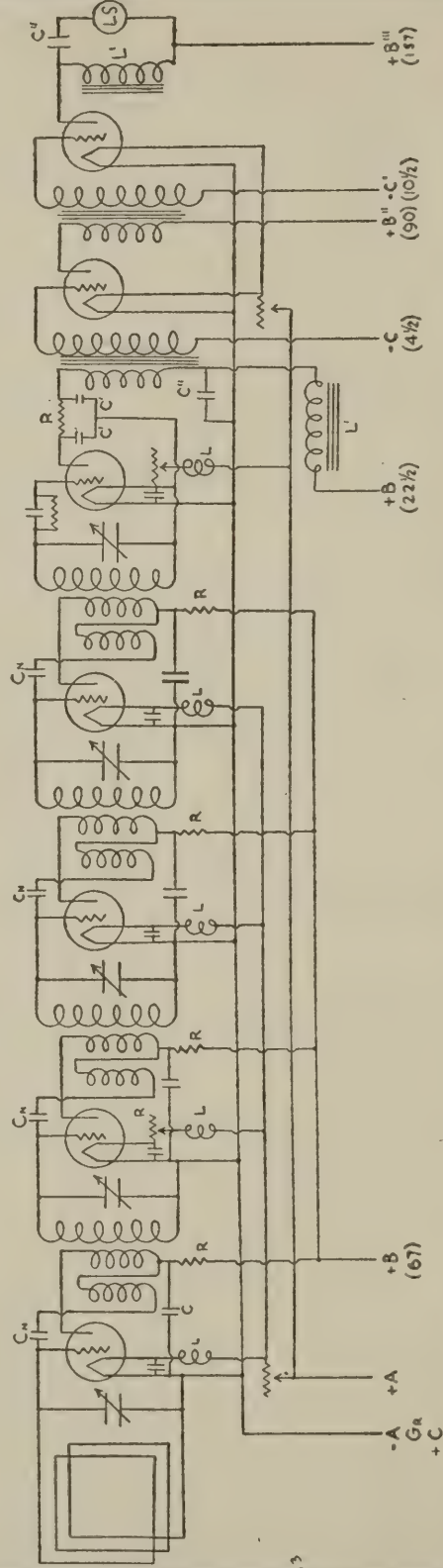


Fig. 113. Four Stage Balanced Tuned Radio Frequency Amplifier with Detector and Two Stage Transformer Coupled Audio Amplifier.
R is a 500 ohm resistor. *C* is a .1 mcf. condenser. *L* is a high frequency choke coil. *C*¹ is a .002 mcf. condenser. These resistances, inductances and capacities act as radio frequency filters to confine the currents belonging to each tube to the circuits of that tube. *C*² is a 2 mcf. condenser and *L*¹ a large choke coil.

part of the receiver than the signal coming in from the antenna or loop and passing through all of the tuned circuits. So shielding is a great aid in eliminating local interference which gets into the set other than through the antenna or loop.

Amount of Shielding Required. Different kinds and sizes of sets necessitate various degrees of care in shielding. In a two stage tuned radio frequency receiver of the shielded type only the coils need to be shielded—those of each transformer in an individual closed can. The lid to the can should have an overlapping edge of about a half inch. For a receiver employing three stages the same degree of shielding may suffice, or it may be necessary to include each tube in the same shield that holds the input coils of that tube. This method is in common practice in the four stage tuned radio frequency receivers that are now on the market. It is also customary to introduce partial shielding around the condensers, but since the only possible kind of coupling here is electrostatic it is not necessary to use tightly closed cans. Small cracks in the shielding which would be very detrimental in the coil shields are of much less importance here. In all cases of shielding the connecting wires that must pass through the shield are run through small holes.

A Four Stage Neutrodyne. Figure 113 shows a four stage tuned radio frequency circuit of the neutrodyne type. Figure 114 shows two stages of the same circuit with the shielding indicated by the shaded outline in the diagram. For convenience, the tuning condensers are shown here in the same shields as the coils; but it is more common to install them outside of the shield in separate partial shielding of their own. This set is shown as a loop receiver.

There are several points of interest about this receiver in addition to those already discussed. The first is the method of keeping the high frequency currents from every stage from flowing through the B battery lines and the battery itself. The method is simple. A resistor of about one hundred to five hundred ohms is placed in the plate circuit and the high frequency current is then bi-passed to the filament through a condenser as shown in the circuit diagram.

All of the shields are mutually connected and all are grounded. In the case of a neutrodyne receiver, one side of the filaments

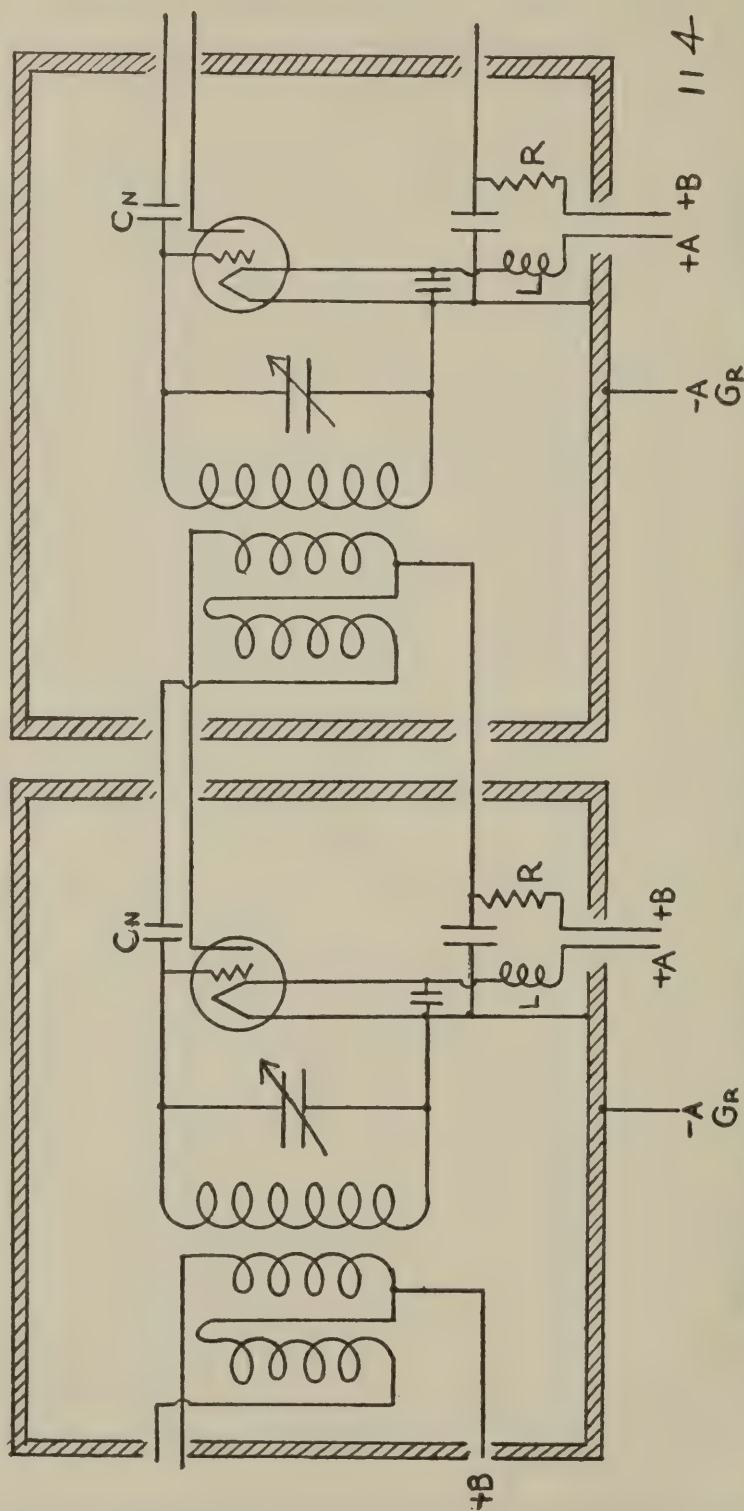


Fig. 114. Two Stages of a Four Stage Neutrodyne showing the Shielding of the Individual Stages

is also grounded. The possibility of interstage coupling through the filament leads or the A battery is eliminated by placing a choke coil in the ungrounded lead of each filament and placing a condenser between this end of the filament and the grounded end. The choke coil is ordinarily only 30 or 40 turns of wire on a rather small tube, say one inch or less in diameter. If the tube does not consume more than .25 amperes a fairly small size wire (No. 30 or smaller) may be used for the choke coil. It is usually wound at random and is several layers thick in order to keep the coil short and in as small space as possible. The bi-pass condensers for the filaments and also for the plate filter circuit discussed above must have low impedance for the frequency of current involved in comparison to the resistance in the plate circuit filter and the choke coil impedance in the filament circuit filter. Dreyer and Manson, in the article referred to at the end of this chapter, recommend condensers as large as 1 mcf. for both these cases. Such large condensers doubtless represent great effectiveness on the part of the filter in which they are employed. It seems to the writer, however, that smaller condensers, say .1 mcf. or even less, might be adequate for most sets of this type.

Special Filters for the Detector Circuits. In sets employing more than three stages of tuned radio frequency it may sometimes become necessary to take special precautions to limit the tendency of the detector to regenerate. In addition to the audio frequency filter used in the plate of the detector circuit and shown in Figure 113 and discussed in connection with Figure 97 in Chapter VI it may be necessary to use a radio frequency filter in the same circuit. Dreyer and Manson indicate a choke coil instead of the resistance shown in Figure 113 for this filter to be put in the plate circuit between the plate of the tube and the primary of the first audio frequency transformer. They employ two small condensers (.002 mcf.) one at each end of the choke and going directly to the grounded shield. This filter takes the place of the ordinary "phone" condenser.

Reduction in Number of Tuning Controls. It may be seen from the diagrams of this chapter that the number

of tuning controls on a two stage tuned radio frequency receiver is three and with receivers employing more stages an additional control comes with each additional stage. If all of the secondary coils are identical and also all of the tuning condensers, it will be possible to fasten all of the condensers except the first together either by belt or shaft or other device and operate all of them from a common control. The tuning of the first condenser is likely to be slightly different from the others due to the differences in the primary circuit coupled to it as compared to the plate circuits in the other cases. Sometimes the first condenser is tuned independently and sometimes it is gang controlled with the others and small adjustments made on its setting with the aid of an auxiliary control.

Types of Tuned Radio Frequency Receivers.

There is a tendency on the part of the public, both manufacturers and consumers, to speak of neutrodyne sets and of tuned radio frequency (commonly called T. R. F.) sets. Many of the first sets of this general type which were produced without Hazeltine's method of balancing or neutralizing employed methods which were more or less inferior to the neutrodyne, and the term "tuned radio frequency" set came to mean a set which was not electrically balanced in any very efficient manner. There are now several sets on the market in which the method of balancing may at least be said to compare favorably with the Hazeltine method. It is hardly fair to classify these balanced receivers with receivers which owe their stability to energy wasting devices. Moreover, since the neutrodyne contains little or nothing to distinguish it from other well balanced sets except its priority in patents, it seems unjustifiable to give it a special name or to treat it as a special type of receiver. It must of necessity be placed in the type of receiver called tuned radio frequency. This class of receivers may be roughly divided into two groups, the one group consisting of sets in which the effects of the grid to plate capacity are actually balanced out, and the other group consisting of receivers in which energy losses are introduced to gain the necessary stability.

The neutrodyne is simply an excellent representative of the first class mentioned above. We have discussed it at great length

because most of its problems (all except the method of obtaining the balance) are common to all types of tuned radio frequency receivers. In the next chapter we shall discuss several other "bridge" circuits and also many receivers employing energy "lossers." We shall spend most of the discussion on the methods of balancing and the devices for introducing losses since the general problems of the tuned radio frequency receiver have already been touched upon in connection with the foregoing treatment of the neutrodyne receiver.

Chapter VII—References

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**RADIO FREQUENCY
AMPLIFICATION
(Continued)**

TOPICAL INDEX

CHAPTER VIII

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CHAPTER VIII

Radio Frequency Amplification

(continued)

IN the last chapter we considered the general proposition of amplifying signals at radio frequencies before using a detector to obtain the audio modulation of the signals. In particular we discussed the merits of radio amplification employing tuned transformers for interstage coupling, and many of the problems arising from the large number of circuits which are tuned to the same frequency in such a receiver. The two principal problems had to do first with making the transformers efficient devices for applying increasingly larger e. m. f.s from stage to stage, and second, with overcoming the tendency of the set to oscillate due to the many opportunities for coupling among so many tuned circuits, either through external parts of the circuits or through tube capacities. In addition to the "neutrodyne" method of balancing the effects of tube capacities we shall now consider several other methods of accomplishing the same result.

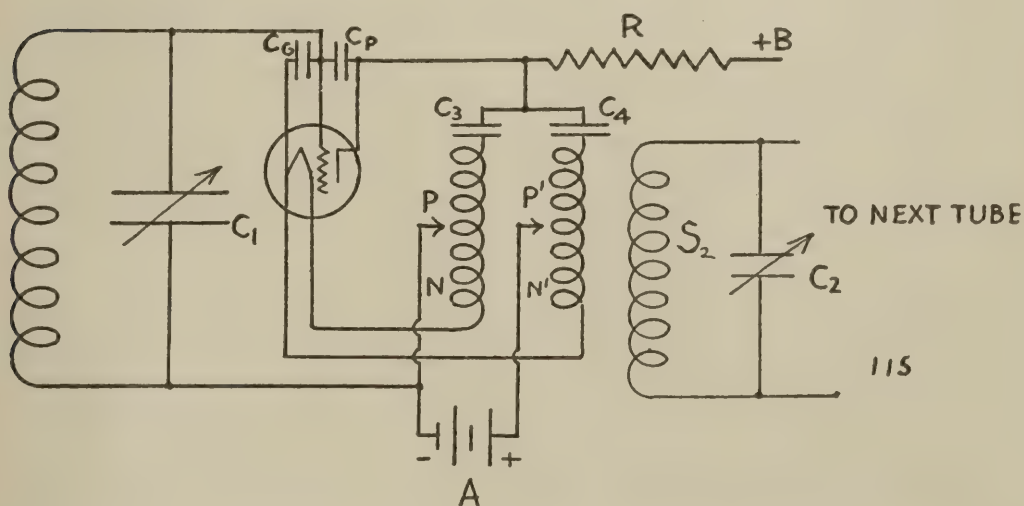


Fig. 115. One Stage of a Balanced Tuned Radio Frequency Amplifier

“Gates” Receiver. Figure 115 shows a single stage of a balanced tuned radio frequency amplifier due to Mr. H. A. Gates. To make all points of the circuit clear the tube capacities are indicated externally to the tube and as before we use the terminology of C_g for the filament to grid capacity, and C_p for the grid to plate capacity. R may be either a resistance or a high frequency choke coil. Its purpose is to keep the high frequency currents out of the B supply and to force them to follow the low impedance paths C_3PN and $C_4P'N'$. The condensers C_3 and C_4 may have any value between .1 and .01 mcf. Their function is simply to keep the high potential plate supply off of the coils PN and $P'N'$ which go to the filament and at the same time permit the high frequency currents to follow this path easily. The coils PN and $P'N'$ have the same number of turns and are wrapped simultaneously, using two wires for the wrapping. The number of turns for each of the two coils may vary from eight to twelve

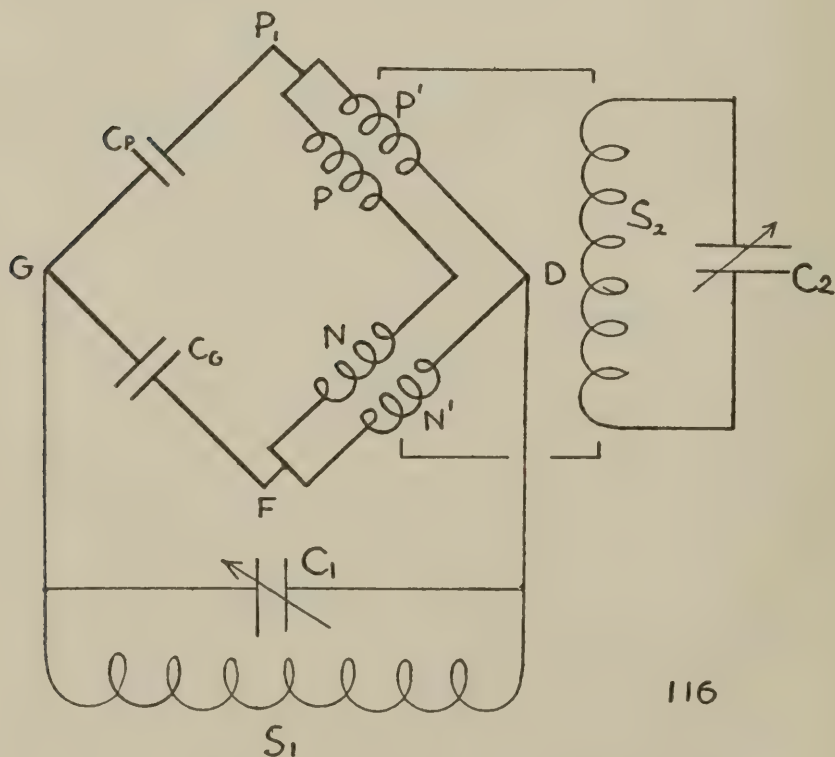


Fig. 116. The “Bridge” of the Preceding Circuit

or more and may be wrapped on the end of the same tube that carries the secondary winding, or they may be wrapped on top of the secondary winding, or they may be wound on a separate and smaller tube and thrust inside the secondary as is common practice in neutrodyne receivers. It is to be remembered that too few turns on these coils will reduce the signal strength especially on the longer wave-lengths (lower frequencies) while too many turns reduces the selectivity. Wrapping these coils on top of the secondary will also reduce the selectivity unless the number of turns is made small or unless the set employs many stages of amplification. Wire of size No. 30 or No. 28 may be used for these coils.

By omitting the batteries and other parts of the circuit not essential to the balance of the "bridge" we may show the fundamental part of the circuit as a true alternating current bridge where the tuned input is applied at two diagonally opposite points and the output of the tube, that is, the input to the next tube, is connected (or coupled) to the other two points of the bridge. If then the bridge is balanced neither of these circuits can feed energy into the other. This bridge is shown in Figure 116. It is interesting to note that C_g is used for one arm of the bridge and no external neutralizing condenser is needed. The bridge is balanced when the following condition is true:

$$\frac{C_g}{C_p} = \frac{P}{N}$$

where P and N include respectively the values of P' and N' .

The balance is made by varying the relative values of P and N and P' and N' by the simple process of tapping these coils at various points for the A battery leads. In factory built sets sufficient uniformity in their construction is possible to enable the builders to attach these leads to the proper turn without actually balancing each individual stage.

Figure 117 shows a receiver employing two stages of amplification of the type just discussed together with a detector and an audio amplifier consisting of two stages of resistance coupled

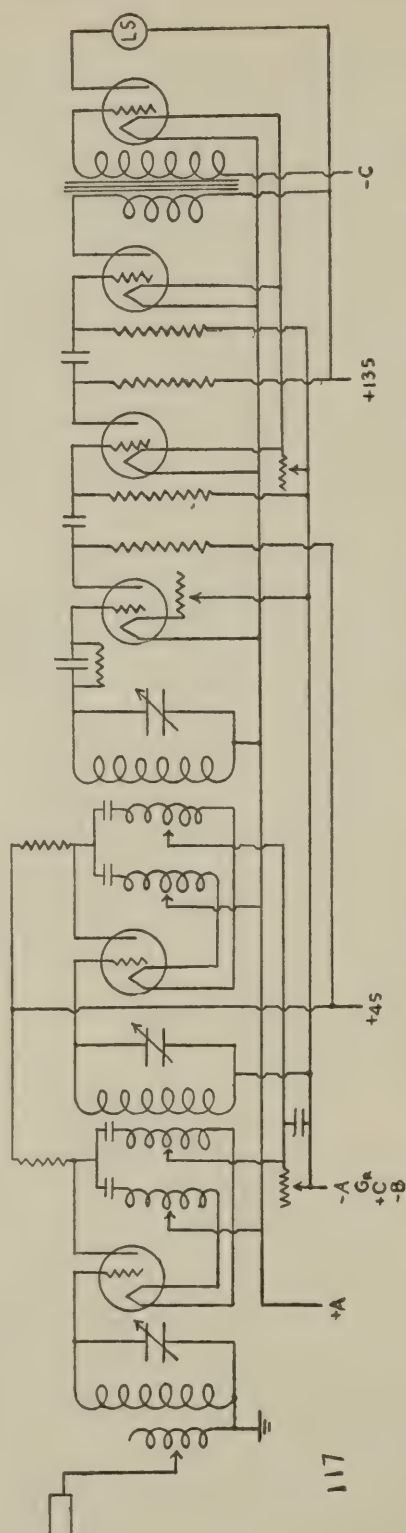


Fig. 117. A Six Tube Receiver Employing Two Stages of Bridge Balanced Tuned Radio Frequency Amplification of the Type Shown in Figure 115

and one stage of transformer coupled amplification. The constants for the audio amplifier circuit details may be the same as those given in the chapter on Audio Amplification. The transformer used here would be of very low ratio, either 1 to 1 or 1 to $1\frac{1}{2}$.

A rheostat in the negative filament lead to the radio frequency tubes controls the filament current through both these tubes and is used as a volume control. In the figure the detector tube has an individual rheostat for its filament control while a single rheostat handles the audio frequency tubes. It is to be noticed that the filaments of the radio frequency tubes of this set are not at ground potential. The negative side of the battery is grounded, but each filament is above ground potential by the IR drop through the radio frequency rheostat and the $I'R'$ drop across the resistance of the coil N . Since the return end of the secondary is grounded it follows that a slight negative potential is kept on the grid. This contributes to the amplification of the tube and helps prevent distortion in the amplification.

The receiver shown has each group of coils individually shielded. When this circuit is used as a multiple stage receiver it is necessary to take the various precautions in shielding and filtering outlined in the general discussion of the last chapter.

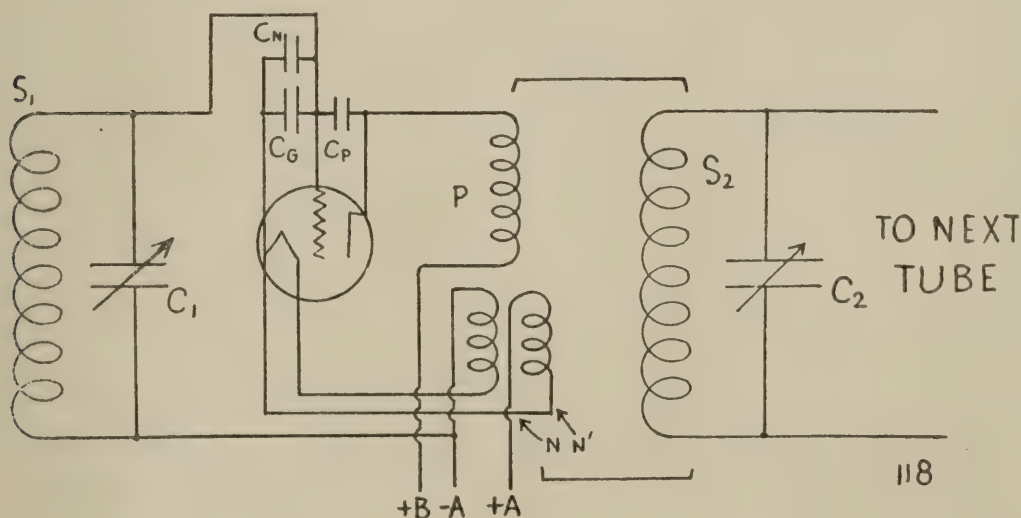


Fig. 118: Another Type of Balanced Radio Frequency Amplifier

Another Type of "Bridge" Receiver. One stage of the next amplifier to be considered is shown in Figure 118. As before, the tube capacities are indicated externally to the tube to make the circuit more evident. The primary coil of the radio frequency transformer consists of about a dozen turns placed in the B battery line in the customary manner. The wire may be quite small, say No. 30 or No. 32. The coils N and N' are in the battery leads of the filament. They should be made of about No. 30 wire and should be wrapped, the two together, near the end of the coil P so that in general appearance the three coils look very much like one continuous coil.

A neutralizing condenser is connected between the filament and grid, and by reference to Figure 119, which is the schematic

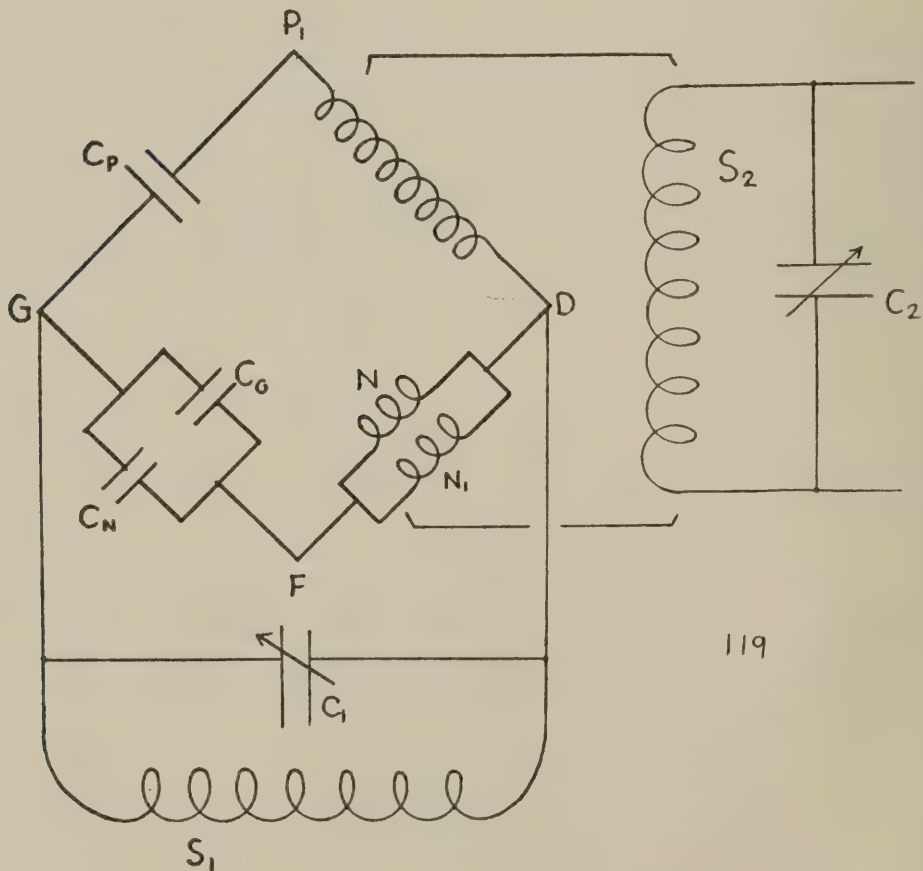


Fig. 119. The "Bridge" of Figure 118

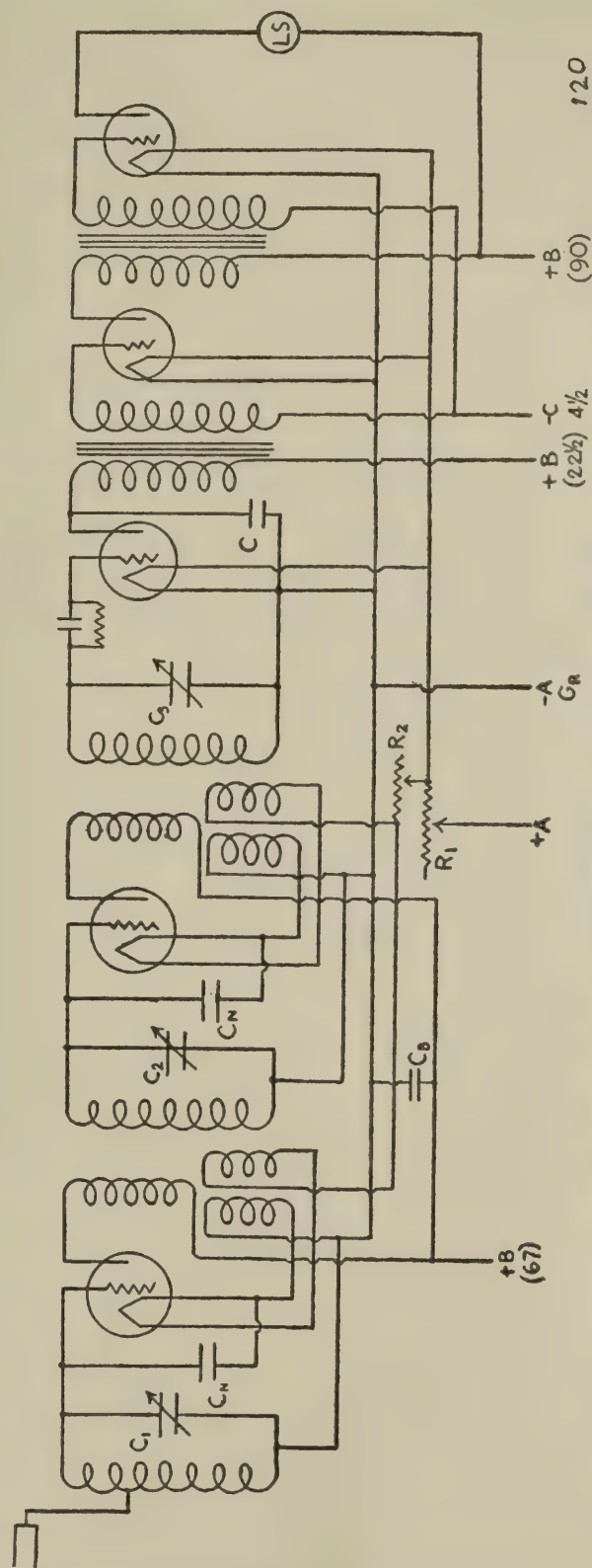


Fig. 120. A Five Tube Receiver Employing Two Stages of Bridge Balanced Amplification of the Type shown in Figure 118. R_2 serves as a volume control. C is the "phone" condenser (.002). C_b has a value of .1 mcf.

bridge diagram for this circuit, we see that this neutralizing condenser added to C_g constitutes one arm of the bridge, the condenser C_p the other capacity arm and the coil P and the coils N and N' the other two arms. The input and output circuits will be isolated from one another when the bridge is properly balanced. This condition will exist when

$$\frac{C_p}{C_g + C_n} = \frac{N}{P}$$

where N includes the inductance due to N' .

Figure 120 shows a five tube receiver of this type where the first two tubes are those of the radio frequency amplifier, the third is the detector and the last two are a standard transformer coupled audio frequency amplifier.

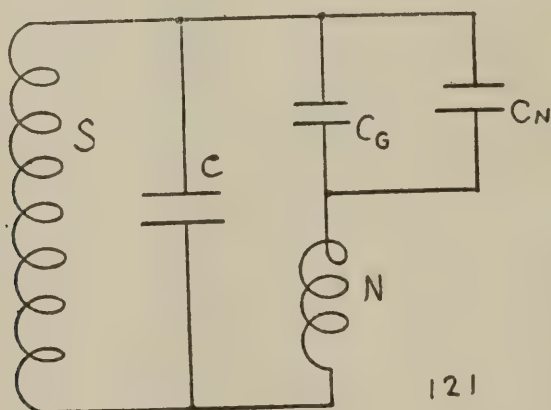


Fig. 121. The Input Circuit of Figure 118

It is to be noted both in this circuit and the preceding one that the capacity C_g does not have the simple parallel relation to the tuning condenser C_1 that it does in the case of the neutrodyne circuit. This point is brought out in the diagram of Figure 121. It is evident that the current through $C_g N$ will not be in phase with that across C_1 as it would be in the neutrodyne circuit.

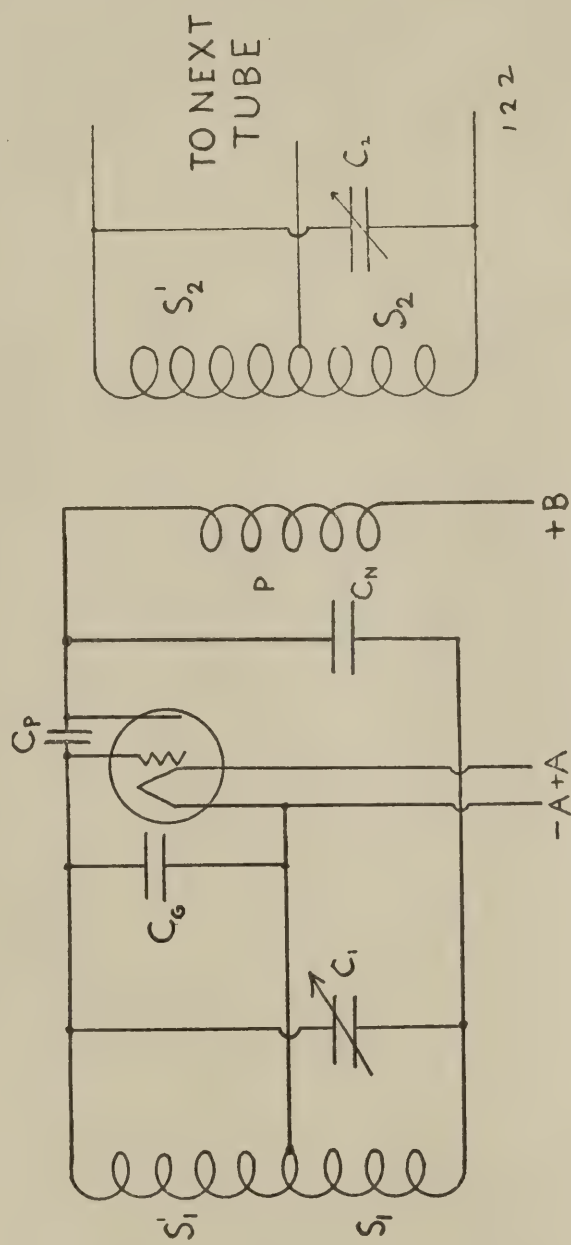


Fig. 122. The "Rice" Circuit

Analysis of this rather complicated circuit shows that the value of E_g , that is the e. m. f. available across C_g for the operation of the tube, is not greatly affected and may even be larger than in the more simple case. This possibility exists due to the fact that the potential drop across the coil N will be almost exactly opposed to that across C_g and the vector sum of the two must equal the potential difference developed across the condenser C . Actually this effect is quite small both in this and in the Gates circuit.

The "Rice" Circuit. Figure 122 shows a single stage of the next circuit to be taken up. It is interesting to note that the radio frequency transformer here presents a somewhat more simple appearance than that of the preceding ones. The secondary coil itself is made to serve as two arms of the bridge. A tap from the midsection of the secondary instead of from the lower end forms the grid return, while the lower end is attached to a neutralizing condenser the other side of which is attached to the plate of the tube. There is nothing at all unusual about the construction of the primary coil and it takes no part in balancing the bridge.

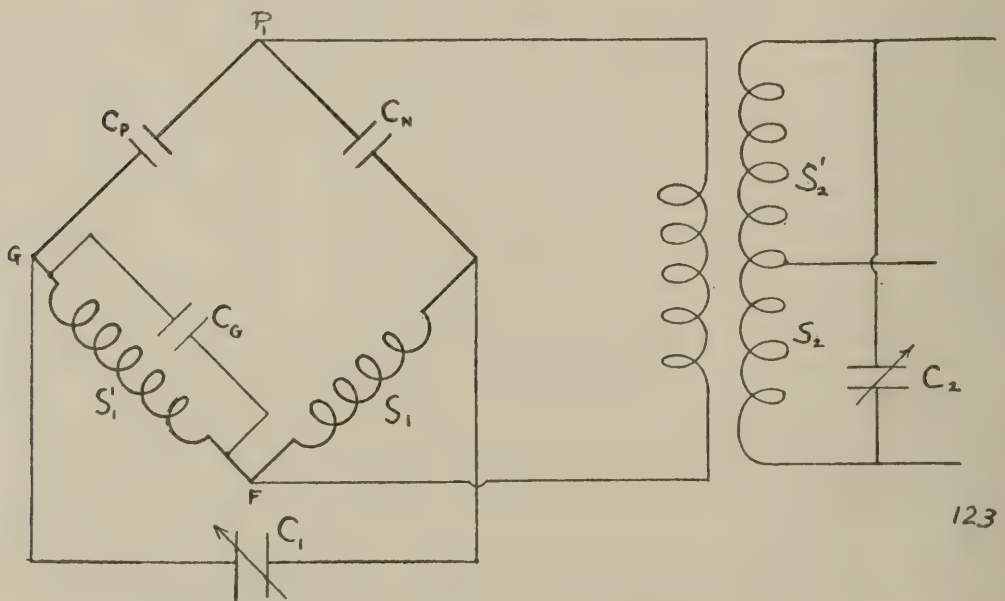


Fig. 123. The "Bridge" of Figure 122

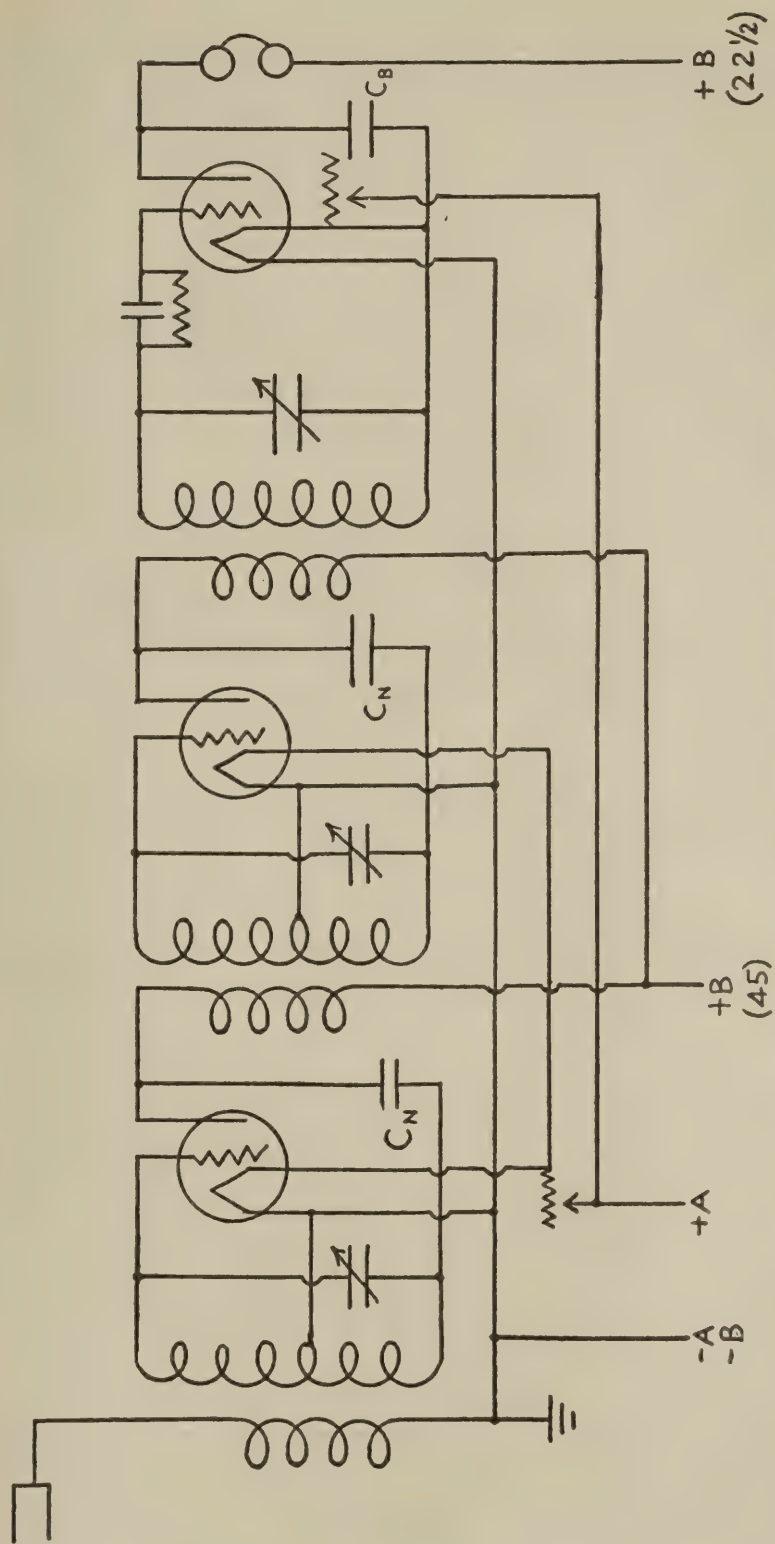


Fig. 124. A Two Stage Amplifier and Detector Employing the Circuit of Figure 122

The schematic bridge involved in this circuit is shown in Figure 123. It is to be noted that the capacity C_g is unavoidably present as a parallel circuit around S_1' so that the expression

$$\frac{C_p}{C_n} = \frac{S_1}{S_1'}$$

does not indicate a perfect balance. Moreover, this balance when once obtained will be a variable with frequency. Fortunately this deficiency in the bridge is not so great as to invalidate its use in the broadcast range. Adjustment of the bridge is accomplished through the small variable condenser C_n .

Figure 124 shows two stages of this type of tuned radio frequency amplifier and a detector. An audio amplifier of any type desired may be used in connection with it. This method of balancing is covered by the "Rice" patent, and has been involved in much litigation between its holders and the holders of the neutrodyne patents.

An All Capacity "Bridge" Circuit. The last bridge circuit to be presented here is shown in Figure 125. Here we have indeed a very simple type of radio frequency transformer. The primary is in its simplest position in the plate circuit and takes no direct part in the balance of the bridge. The

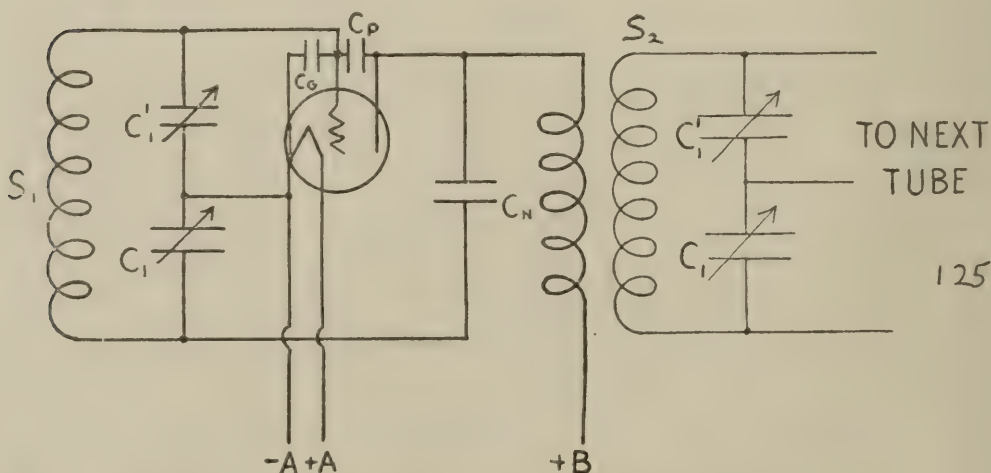
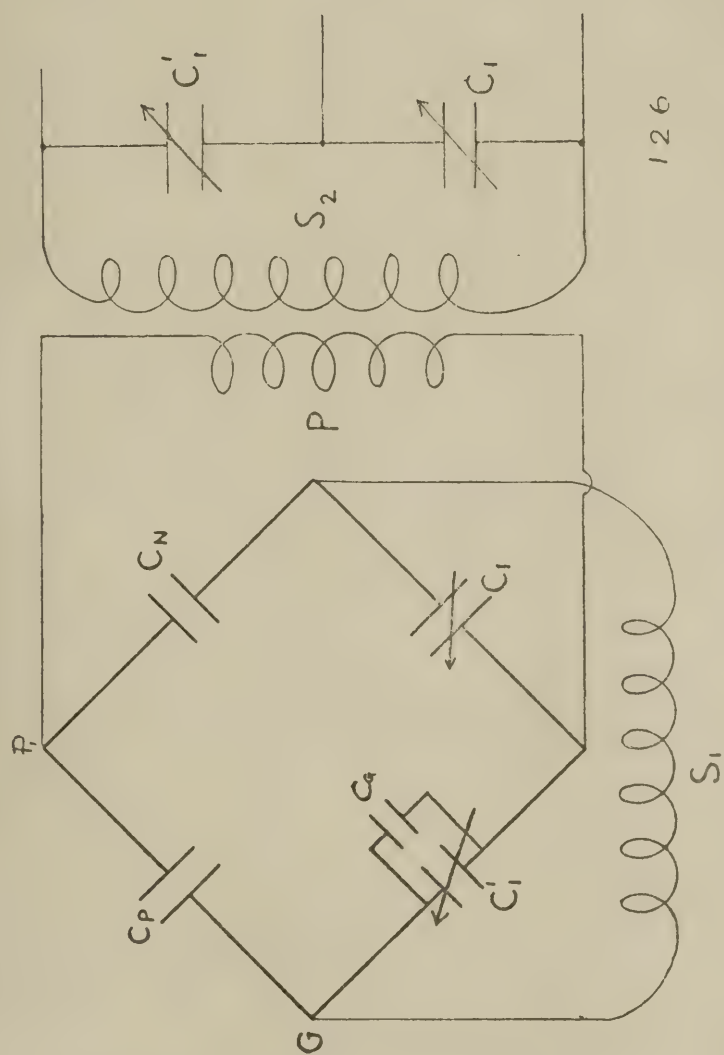


Fig. 125. One Stage of the All Capacity "Bridge" Circuit



126

Fig. 126. The "Bridge" of Figure 125

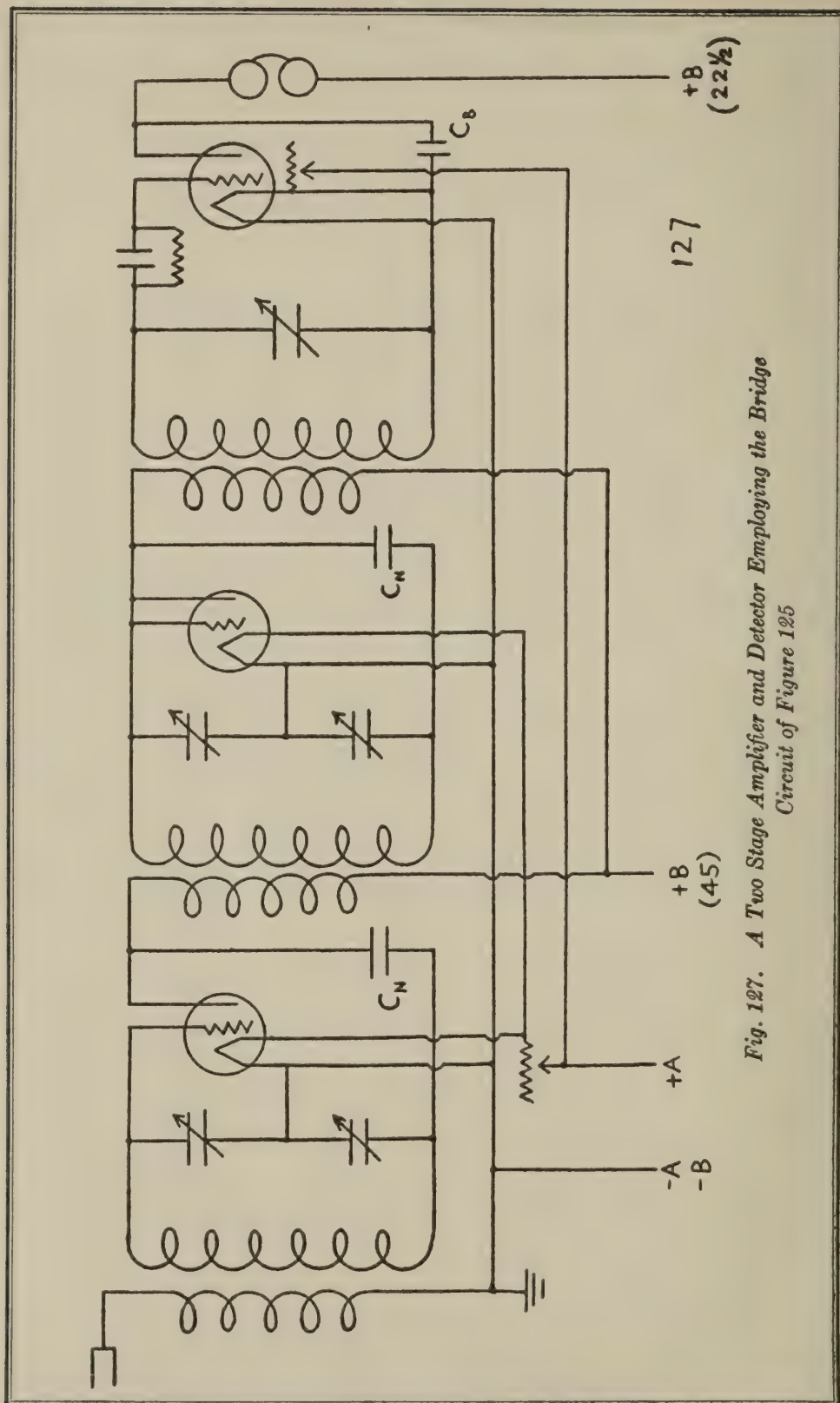


Fig. 127. A Two Stage Amplifier and Detector Employing the Bridge
Circuit of Figure 125

unusual feature of the circuit is the split tuning condenser C'_1C_1 . These two condensers are mounted with their rotors on the same shaft so that they turn together with the motion of one dial. They are connected in series as shown and connection to the filament of the tube is made from the connection between the two condensers.

Figure 126 shows the bridge analysis of this circuit. We see at once that all four of the bridge arms are capacitive rather than inductive. For a condition of balance we must have

$$\frac{C'_1 + C_g}{C_1} = \frac{C_p}{C_n}$$

and since C_g is small in comparison with C'_1 this is approximately equal to

$$\frac{C'_1}{C_1} = \frac{C_p}{C_n}$$

Of course the values of C'_1 and C_1 change as one tunes from one frequency to another, but since the rotors of these condensers are attached to the same shaft the ratio

$$\frac{C'_1}{C_1}$$

does not change. So when a balance has once been obtained by means of the small variable condenser C_n the bridge remains balanced through the broadcast range of frequencies.

If the condensers C_1 and C'_1 are equal, it is apparent that only one-half the e. m. f. developed across S_1 will be impressed across the grid to filament of the tube. If, however, C_1 is made larger than C'_1 a higher fraction of the total e. m. f. across S_1 will be delivered to the input of the tube. It is to be remembered that the value of these condensers (in series) for tuning the coil S_1 will be less than the value of the smaller of the two condensers.

If C_1 should be made with a capacity of .00070 mcf. and C'_1 with a capacity of .00035 the value of the two in series would be about .000234 mcf. Since the bridge itself balances very well it would probably be possible to use this rather small value of tuning condenser and a correspondingly larger value of S_1 than is customary in most circuits. In the case of the values chosen, although only about two thirds of the e. m. f. across S_1 would be available across the tube, yet the actual value would be about the same as that obtained from a simple tuned input using a smaller value of S_1 and a single .00035 mcf. condenser.

Figure 127 shows two stages of this type of amplification with a detector. Any type of audio amplifier may be added to complete the set.

There is one point to be remembered among the details of this set, and that is that in the circuit as shown here the grid and the secondary are "floating." That is, their connection with the rest of the circuit is entirely through condensers. The grid will tend to go negative due to an accumulation of electrons on it. It is desirable to have the grid take up a slight negative potential, but if it goes too far there may be a tendency to block the tube. This condition can be remedied by tying the grid to the filament with a large grid leak, say 5 megohms, or larger. If the grid leak is large it will not seriously affect the balance of the bridge.

The four circuits discussed above together with the neutrodyne of the previous chapter are fairly representative of the best balanced tuned radio frequency receivers. There are many others some of which compare favorably with those discussed, but most of which are less successful. It is to be remembered that the motives for bringing out new circuits are frequently not those for improving old circuits, but rather for making different circuits. If one can devise a different circuit he may be able to free himself from the patent restrictions of other manufacturers. Or, if he be a manufacturer of parts rather than sets, he may be able to make the public believe that his new and different circuit is superior to others and so create a demand for his product. Or perhaps the advocate of a new circuit is just a clever magazine writer who has become adept at drawing old circuits in new ways, and so he keeps him-

self supplied with material about which to write. A "different" or "new" circuit is not necessarily better than an old well known one. Many of the "new" tuned radio frequency circuits for which certain manufacturers have been trying to sell us parts during the last two years are very complicated looking as compared to the circuits given in these two chapters. The writer does not doubt that these circuits work, and perhaps work rather well, but the more he sees of them the more convinced he is that they represent no improvements over the more or less standardized types of circuits here shown and that the only advantage of the extra apparatus for the complicated circuit lies in the profits to the manufacturer.

Other Methods of Stabilizing Radio Frequency Amplifiers. We come now to a class of tuned radio frequency circuit in which stabilization is effected through the introduction of energy losses at the proper places to prevent oscillations from occurring. The idea of purposely introducing losses may seem heretical at first; but actually the amount of loss necessary to introduce into the grid circuit to suppress oscillations need not be sufficient to materially reduce the e. m. f. applied to the grid-filament of the tube. The chief difficulty lies in applying a loss device whose action will be equally good over the necessary frequency range. A large part of the virtue of the "bridge" balanced receivers lay in the independence of the balance to frequency. It is not difficult to find an energy loss device whose dissipation is independent of frequency, but unfortunately the tendency of the tube to oscillate is not independent of this quantity but is much greater for the high than for the low frequencies. There are two principal methods of introducing losses, one by the judicious placement of resistance in the circuit, the other by magnetic coupling with auxiliary energy consuming circuits. In addition to these true loss devices there are several methods in vogue which simply reduce the efficiency of the entire amplifier to the point where it will not oscillate. We shall consider some of the ways for using pure resistance first.

Resistors for Obtaining Stability. Figure 128 shows a six tube receiver in which there are two stages

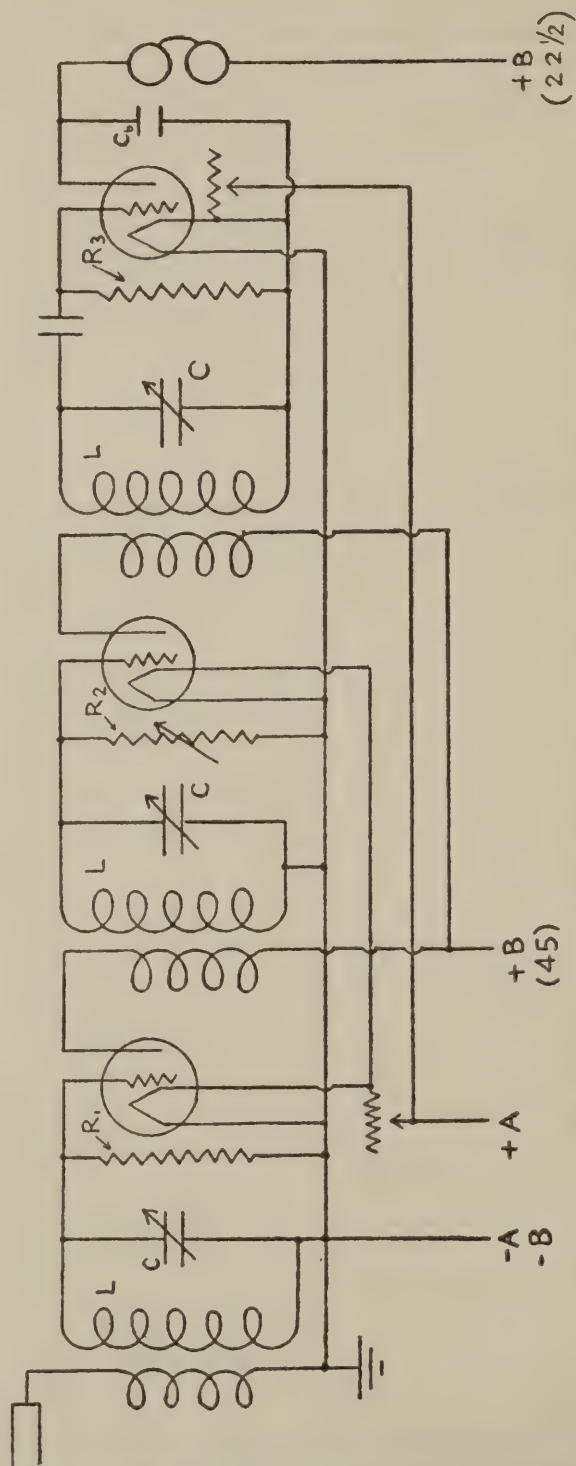


Fig. 130. Another Radio Frequency Circuit Using Resistors for Stabilizers.
 $R_1 = R_2 = 100,000$ ohms. R_3 is a variable resistor of from 0 to 100,000 ohms

of tuned radio frequency, a detector and three stages of very low ratio transformer coupled audio amplification. The fact that there are three instead of two stages of audio amplification compensates for the extremely low ratio of the transformers. As has already been pointed out, it is far more economical to make

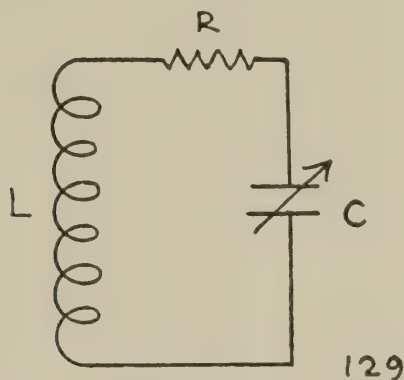


Fig. 129. Incorrect Use of Resistance for Stabilizing the Amplifier

good low ratio than good high ratio audio transformers. Assuming that the transformers in this set are well made it is to be expected that the quality of the audio frequency amplification will be good.

The resistances R_1 and R_2 are fixed resistors of from 100 to 500 ohms, a value which is small in comparison with the impedance of the tube capacity C_g at the frequencies in the broadcast range. Yet this resistance will limit the *amount* of energy fed from the plate circuit to the tuned secondary sufficiently to prevent oscillations. The device is an equal absorber for all frequencies and so must be of the right value to permit considerable regeneration on the higher frequencies (shorter wave-lengths) in order that it may not reduce the signal strength on the lower frequencies by absorbing more of the original signal from the secondary than is fed back into this circuit from the plate circuit. This method of introducing loss between the input and output circuits does not materially affect the sharpness of tuning of the input nor the value of the e. m. f. of the tuned secondary which is applied across C_g . These good features of the method offset to some extent the fact that the stabilizing effect is not quite uniform through the broadcast range of frequencies.

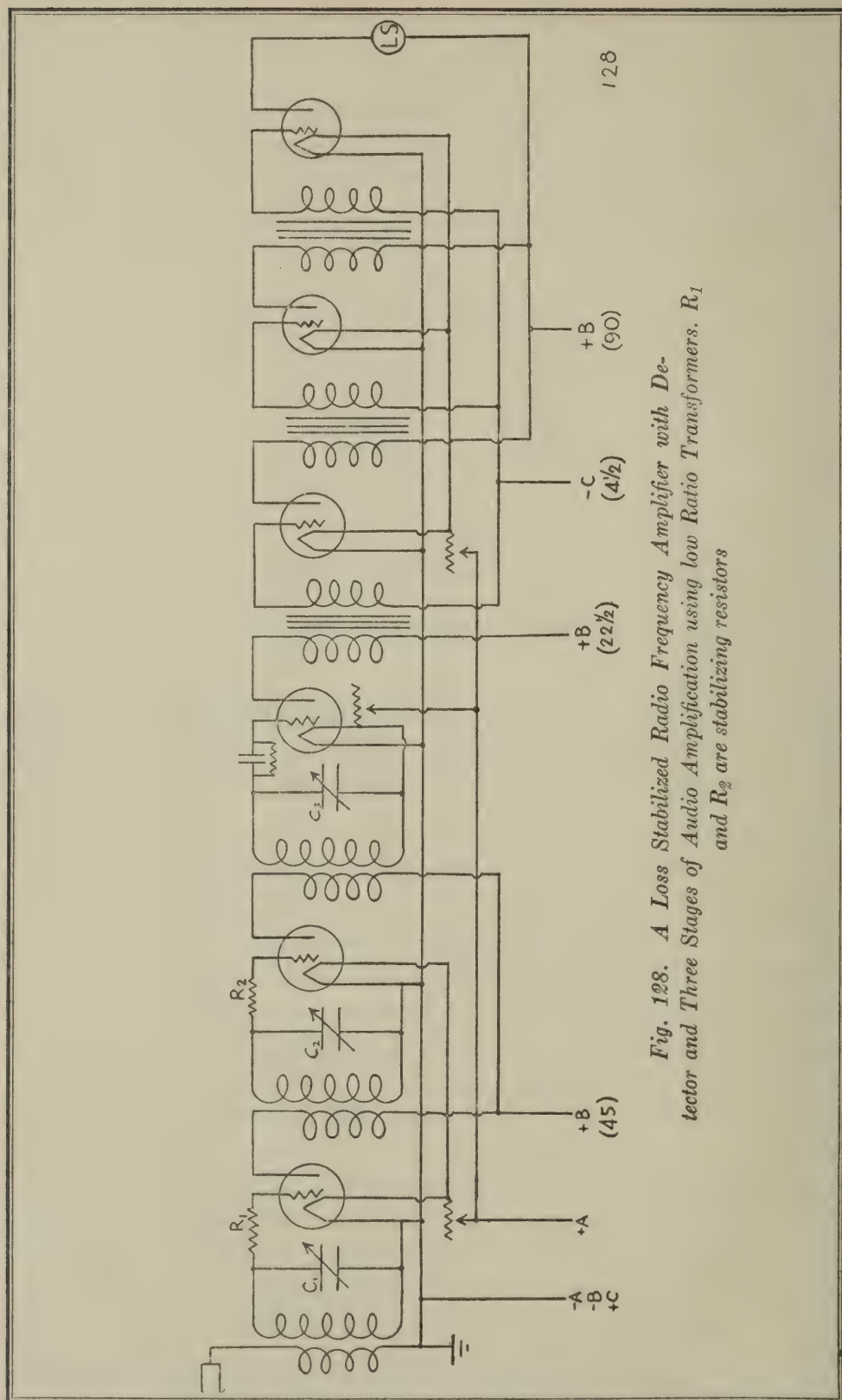


Fig. 128. A Loss Stabilized Radio Frequency Amplifier with De-tector and Three Stages of Audio Amplification using low Ratio Transformers. R_1 and R_2 are stabilizing resistors

It is to be noted that the resistance in the above circuit is not included in the LC circuit as indicated in Figure 129. Resistance introduced in this manner will not only greatly broaden the tuning but will also decrease the e. m. f. developed across L.

Grid Leaks and Stabilizers. In Figure 130 we have another radio frequency amplifier employing resistance as a means of stabilization. Only the two stages of radio frequency amplification and the detector are shown in the diagram, and any type of audio amplification desired may be added to make the receiver a loud speaker type. It is generally true that in a two stage tuned radio frequency receiver the second stage of amplification is more likely to oscillate than the first stage or the detector. If an aperiodic primary is used as is quite common now, the natural frequency of the antenna circuit will be much higher than the frequencies to which the set will be tuned. This circuit will tend to absorb some energy from the first tuned secondary and so slightly reduce the tendency of that circuit to oscillate. The detector with its slightly positive grid and its untuned output circuit feeding into an untuned circuit will also be less likely to oscillate than the second radio frequency amplifier circuits. Hence in this receiver we place large resistors (really used as grid leaks) as shown in the diagram in the circuit of the first tube and that of the detector. The value of each of these resistors may be about 100,000 ohms. If the resistor on the second tube circuit be made a variable one, it will be possible to permit and control regeneration on this stage. The resistance should have a high value of about 100,000 ohms and a minimum value as small as may be obtained in this type of variable resistor.

These resistors may be thought of as making the tuning condensers leaky, and hence reducing the efficiency of the tuned circuit LC. It may seem simpler to think of them as shunt resistances about C_g thereby increasing the alternating current drawn from the terminals of L and so decreasing the e. m. f. across L. Of course the loss in volume and in selectivity is partially compensated for by permitting the second stage to regenerate rather strongly. It is to be remembered, however, that if this stage is permitted to oscillate, the first stage will quite probably

oscillate also and prove as disturbing to one's neighbors as the much cursed simple regenerative receiver.

Inductive "Lossers." One of the simplest ways of introducing losses by induction is to place a few turns of wire on top of or close to the secondary and to short circuit this coil

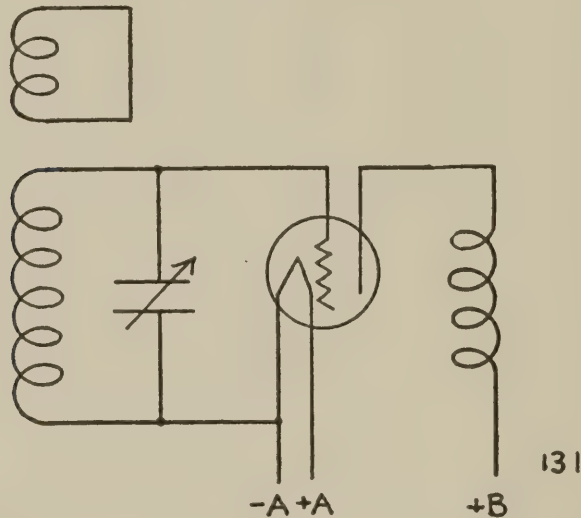


Fig. 131. An Inductive Energy Absorber to Stabilize a Stage of Tuned Radio Frequency Amplification

on itself. One stage of such an arrangement is illustrated in Figure 131. If this coil is arranged to suppress oscillations on the high frequencies where the tendency to oscillate is great, it will almost certainly absorb enough energy on the low frequencies to reduce the signal strength to an objectionable degree.

Figure 132 shows a modification of this inductive loss method where the ends of the coil are fastened to a small fixed condenser. If the coil has about half the number of turns as the secondary and the condenser a value about one-half that of the maximum capacity of the tuning condenser, this circuit will be resonant at the lower wave-length (upper frequency) end of the broadcast range. In this region it will absorb much more energy from the tuned secondary than at the lower frequencies. This is the desired condition for absorption at the various frequencies since the tendency

to oscillate is least on the low frequencies. This coil of wire may be wrapped on a separate tube and slipped into or on the secondary or it may be wrapped on the same tube with the secondary. Of course the degree of absorption of this device does not vary precisely as the tendency of the circuit to oscillate, but its variation

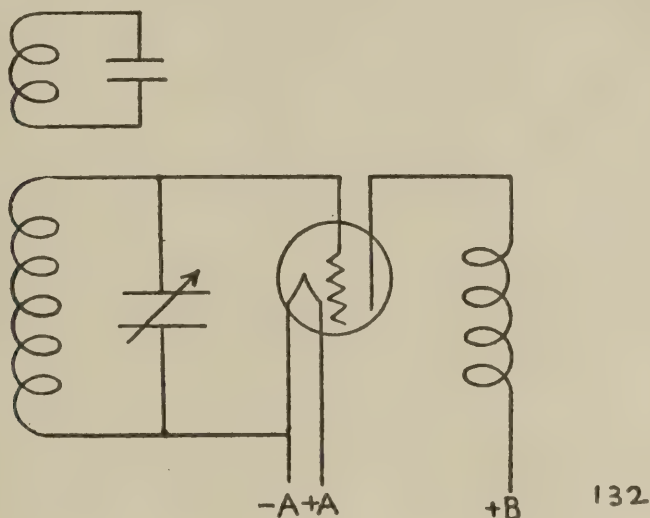


Fig. 132. An Inductive Stabilizer Which Does Not Suppress the Lower Frequencies

is in the right direction and on the whole it is a fairly successful method of loss stabilization.

Eddy Current Loss Method. Another method, related to the first in this group, consists in mounting the secondary coil close to the tuning condenser. The metal end piece of the condenser serves very much as the closed coil in the receiver referred to. Eddy currents are set up in this metal plate by the changing magnetic field of the current in the secondary. It is obvious that the general efficiency of the coil is greatly impaired in this manner. In fact, in bridge balanced sets great care is taken to keep metal away from the open ends of the coils when they are mounted in the open and when enclosed in shielding, the shields are made very much longer than the coils so as to keep the metal away from the ends. It is also evident that if the coils are close enough to the metal ends

of the condensers to prevent oscillations at the shorter wave-lengths, the longer wave-length stations will be reduced in strength.

Stabilization by Varying the Over-All Efficiency of the Amplifier. Of the methods which accomplish stabilization by a general reduction in the efficiency of the

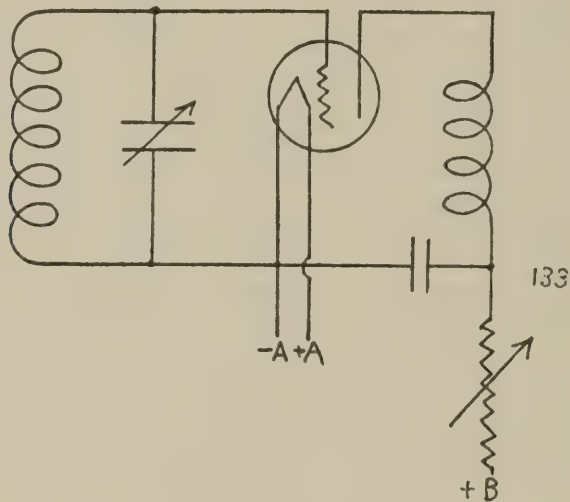


Fig. 133. A large variable resistor in the plate supply may be used to control the oscillating tendencies of the circuit

amplifier we have already considered the use of the potentiometer. Another method which has been used on some of the lower priced commercial sets is based on dependence on the rheostat controlling the filaments of the radio frequency tubes and hence varying the electron emission of these filaments. Still another method is shown in Figure 133 where a variable resistance has been placed in the B battery lead which supplies the plate of the tube. Sometimes the same variable resistor is made to control the plate currents of both tubes. This latter method permits of undesirable intertube coupling through this common resistance.

In all of these three methods of controlling the efficiency of the amplifier there is a great tendency on the part of the operator

to permit the set to oscillate until he finds the desired signal by the whistling beat note method employed in the operation of simple regenerative detectors. After locating the signal he brings the stabilizer into action and finally gets off the air, as we say when a broadcasting station stops transmitting. These oscillating tuned radio frequency sets can cause more disturbance than any regenerative detector unless the detector circuit happens to be of the tuned antenna type.

The foregoing account of loss stabilization is not complete but is fairly representative of both good and bad ways of employing losses for reducing the tendencies of receivers to oscillate. Some attempt has been made to point out the virtues and failings of the various schemes. It is interesting to note that a few receivers on the present day market employ combinations of two or more of the methods discussed above.

Coils and Coil Construction. A great deal concerning the nature and construction of coils for use in the various parts of tuned radio frequency sets has been said in the course of the discussion of various kinds of sets. A few other suggestions will be added here.

Shape of Coils. Since broadcasting came to us a few years ago we have been deluged with all kinds and shapes of coils made in all sorts of fancy designs and of various sizes of wire from very small to very large—all designs masquerading under the magic words “low loss.” We may finally be led to ask, what is a low loss coil? The ideal coil should have as little distributed capacity as possible and as small ordinary resistance as possible and no absorption either to the insulation on the wire or the form which holds the wire. It is interesting to the casual observer, and a great boon to the manufacturer of sets, that measurements made in many different radio laboratories show that for the size coils needed in broadcast receivers the simple straight single layer solenoid type approaches nearest to the ideal. What a blow to the exponents of various kinds of spider web and basket weave and diamond weave and toroidal coils!

Size and Spacing of Wire. Considerable latitude in the size of wire used on the solenoids is permissible, there being little difference in the efficiency of the coils for wire sizes between 20 and 26. It might at first be thought that wire larger than 20 would have less resistance, but we are interested in the effective resistance at high frequencies rather than the resistance as measured with direct current. It is well known that the effective resistance of a conductor does not remain constant when high frequency currents are used instead of low frequency currents and that this effect is more evident for conductors of large area of cross section than for small ones. This increase in resistance with frequency is caused by the so-called "skin-effect," references to which are given at the end of this chapter. The import of these facts is that little or nothing is to be gained by using wire larger than 20. Wire as small as 28 is sometimes used, especially for small coils which it is desired to shield in a limited space—otherwise 26 is about the limit.

Coils may be made by using double cotton covered copper wire and letting the cotton insulation serve as the spacing between successive turns. This method does not give quite sufficient spacing nor does it give sufficient uniformity because of the softness of the insulation. It is much better practice to use either bare or enameled wire and to space it either by threading the tubing or by automatic machine winding. Spacing of about the thickness of the copper wire itself is ordinarily used—a little less than this for the larger sizes of wire.

Size of Coils. There seems to be considerable diversity of opinion among reputable radio engineers as to the exact dimensions to make coils for the secondaries of tuned radio frequency transformers. Perhaps the most commonly used size of tubing in the past has been about $2\frac{3}{4}$ or even 3 inches in diameter. Such a size using 22 or 24 gauge wire gives a winding for the broadcast range of somewhere near the same length as the diameter of the coil. However, if one desires to enclose such a coil in copper shielding he discovers that the shield needed is rather larger than he may care to use. Consequently we find on many of the newer sets coils of $2\frac{1}{2}$ inch diameter or even less wound with 26 wire and occasionally 28, thus reducing the length of the coil. The disadvantages

arising from the use of the smaller wire with smaller spacing are largely offset by the advantages gained in the shielding. As usual we are obliged to adopt the best compromise.

It is to be remembered, however, that the resistance of a circuit is contributed to by the resistance in any circuit which is inductively coupled to it. So that the efficiency of a well built secondary may be somewhat impaired by closely coupling to it a primary made of extremely small wire.

It is, nevertheless, possible to make a tuned radio frequency transformer with such small losses that it will tune too sharply. That is, the frequencies three or four thousand off from the carrier will be handled with less efficiency by the transformer than the carrier frequency to which it is tuned. The result will be a loss in the high tones and a general lacking in brilliance of the audio signal. An interesting, but rather technical discussion on improving the selectivity without impairing the fidelity of amplification over a sufficient band of frequencies to save the high notes will be found in an article by Professor Hazeltine in the number of the *Proceedings of the Institute of Radio Engineers* in the reference list at the end of this chapter.

Toroidal Coils. Toroidal coils, although old to scientists, were presented to the public a few years ago as something new and more or less as a panacea for all the ills of undesirable couplings in a radio receiver. It is true that a well made toroidal coil has no external magnetic field and hence can be placed in any position with respect to another similar coil without being coupled with the same

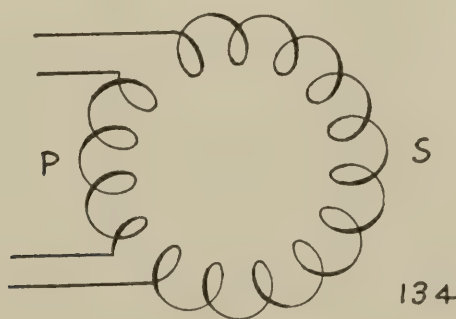


Fig. 134. A Coil which looks like a Toroid but is really two Coils each with open Ends

(except of course when one coil is wrapped around the other). Also, these coils are immune to electro-magnetic pick-up. It must be pointed out that all coils which look like toroids are not necessarily so. Consider the coils of Figure 134 which are wrapped to look like a continuous toroid. It is obvious that neither the primary nor

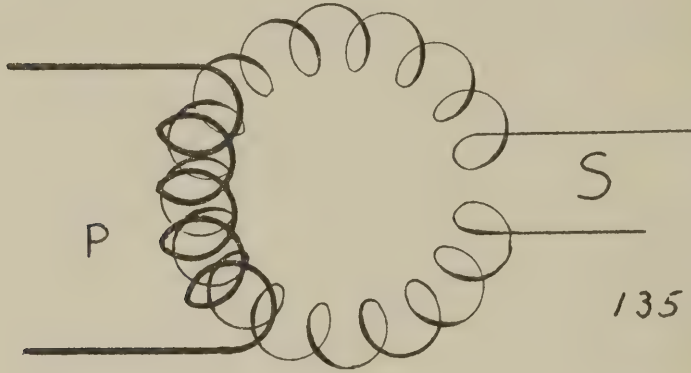


Fig. 135. A true Toroidal Secondary with an Ordinary Primary

the secondary is toroidal. Or consider the coils of Figure 135 where a true toroidal secondary is coupled with a primary which is not toroidal. The primary can pick up energy from stray magnetic fields or electro-magnetic radiations and it can feed these "strays" into the perfectly good toroidal secondary. To gain the full advantage of the closed field of a toroid it is necessary to have a complete toroid for each coil involved in the group of coils used.

So far as the losses of a toroid are concerned they are comparable with the losses of a coil of similar diameter straightened out as an ordinary solenoid. In practically all cases this will give a coil which is long in comparison with its diameter, and this type of coil has more resistance and distributed capacity in comparison to its inductance than the type of solenoidal coils recommended in a previous paragraph. Actual measurements on toroidal coils bear out these predictions. This discussion of toroidal coils is not intended as entirely condemnatory, for these coils will undoubtedly fill a useful place where closed fields without the complications of shielding are desired. The user of transformers made in toroidal

shape should, however, make certain that he is really obtaining toroids. He should also remember that varying the coupling between a true toroidal primary and toroidal secondary is not a simple process. The coupling is inherently one to one. The coupling may be reduced by putting only part of the necessary inductance in the secondary which is coupled to the primary and putting in series with this toroid another toroid containing the remainder of the inductance necessary for the tuned part of the transformer. This method of varying the coupling of circuits where all the inductances are toroidal is an application of well known theory in coupled circuits and is due to Morecroft.

The last two chapters have dealt with one of the most important types of radio receivers, now in general use, namely, tuned radio frequency receivers. The next chapter will be concerned with another important type, superheterodynes, and also with receivers employing certain combinations of circuits already discussed.

Chapter VIII—References

Radio Frequency Transformers in Multiple Stage Receivers

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**SUPERHETERODYNES AND
COMBINED CIRCUITS**

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CHAPTER IX

Superheterodynes and Combined Circuits

THE great difficulty with amplification at radio frequencies for all cases except where tuned inputs are used is that the grid to filament capacity C_g tends to short circuit the repeating device, be it the secondary of a transformer, a resistance, or a simple inductance. Amplification at radio frequency is, however, desirable because it increases the ratio of signal to noise, and because the detector tube responds in proportion to the square of the applied signal voltage. An ingenious arrangement for increasing the efficiency of amplification without losing the good features of amplifying at radio frequencies was devised by Mr. E. W. Armstrong.

We are familiar with the whistling beat note produced between an oscillating detector and an incoming high frequency signal when the two differ in frequency a little. We are also familiar with the same sort of whistle heard through a non-oscillating detector when some other nearby detector is oscillating at a frequency near to that of the station signal. Let us suppose that we have a simple non-oscillating detector connected to an antenna and suppose that we have an oscillating set nearby with one of its coils slightly coupled to the simple detector. We shall have the detector circuit tuned for the frequency of some incoming signal and then vary the tuning on the oscillating set. We will of course get the customary whistle resulting from the detector rectifying the two signals and so giving us a tone fixed by the beat frequency. As we turn the oscillator so as to remove its frequency farther from that of the signal the beat note rises in frequency, being equal to the difference of the two high frequencies. Moreover, this beat-

note will have its amplitude varied by the audio modulation of the incoming signal. Another way to look at this state of affairs is simply to remember that the incoming signal is not a single frequency but is a band of frequencies made up of the carrier frequency plus and minus the audible frequencies.

Let us suppose that we adjust the oscillator until the beat frequencies become so shrill as to pass beyond the limit of hearing. For convenience, let us suppose that the beat frequency with the

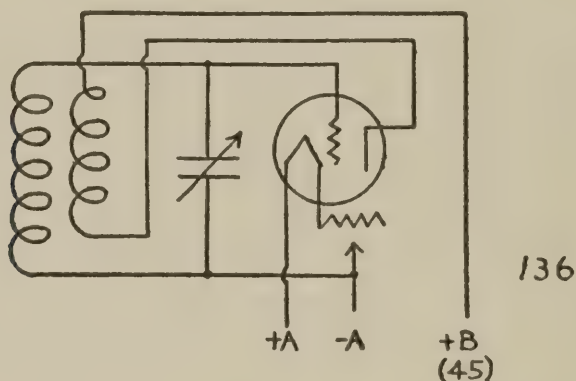


Fig. 136. Standard Oscillator—inductive feed-back type

carrier is 50,000 and the various side band frequencies extend from about 45,000 to 55,000. This set of frequencies may now be passed through a multi-stage amplifier with much greater efficiency than the original high frequencies of the broadcast range and may finally be delivered to another detector which delivers the audio modulation of the original signal to a pair of telephones or to an audio amplifier for loud speaker operation.

Oscillators for Superheterodynes. Two types of oscillating tube circuits are in common use for providing the local high frequency. The first, shown in Figure 136, is exactly like the circuit of an inductive feed-back regenerative receiver, except that usually no grid condenser or leak is used and the grid return goes to the negative side of the filament instead of the positive side. This circuit is in general satisfactory, but it

does not oscillate quite as readily on the low frequencies as on the high frequencies. This feature could be improved by making the tickler coil T movable so as to vary its coupling with S, but the addition of controls is highly undesirable.

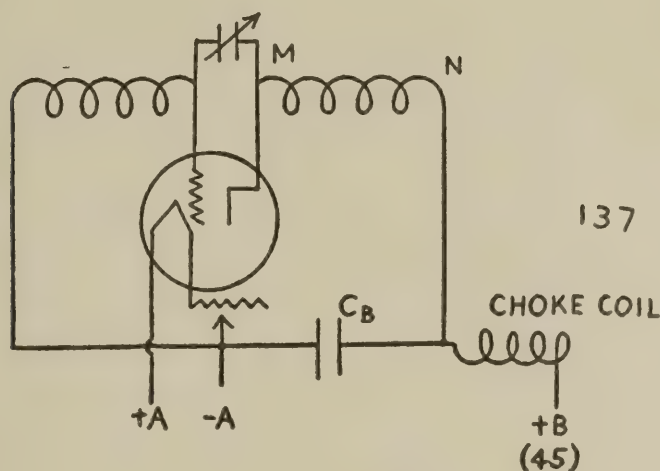


Fig. 137. Standard Oscillator—"Hartley" type

The more commonly used oscillator is shown in Figure 137. Reference to Figure 138 may make this appear somewhat more like a tuned circuit than appears from a casual glance at Figure 137. Ordinarily the two coils are wrapped on the same piece of tubing and are about equal. This division of the inductance is not the most efficient, but efficiency of an oscillator as a producer of power is not a requisite for superheterodyne purposes. It is to be noted that coupling between the two coils is not at all necessary, since any irregularity in the plate current will cause a potential variation across the inductance M N. This is equivalent to applying an e. m. f. at two points of a tuned circuit and will give rise to oscillations in that circuit with frequency fixed by the constants of the circuit. An oscillator of this type will require coils which together contain about fifty-five turns if wrapped on a tube $2\frac{3}{4}$ inches in diameter and when used with a .0005 mcf. condenser. A fixed resistor of from 100 to 500 ohms may be substituted for the choke coil. In fact the oscillator will work without

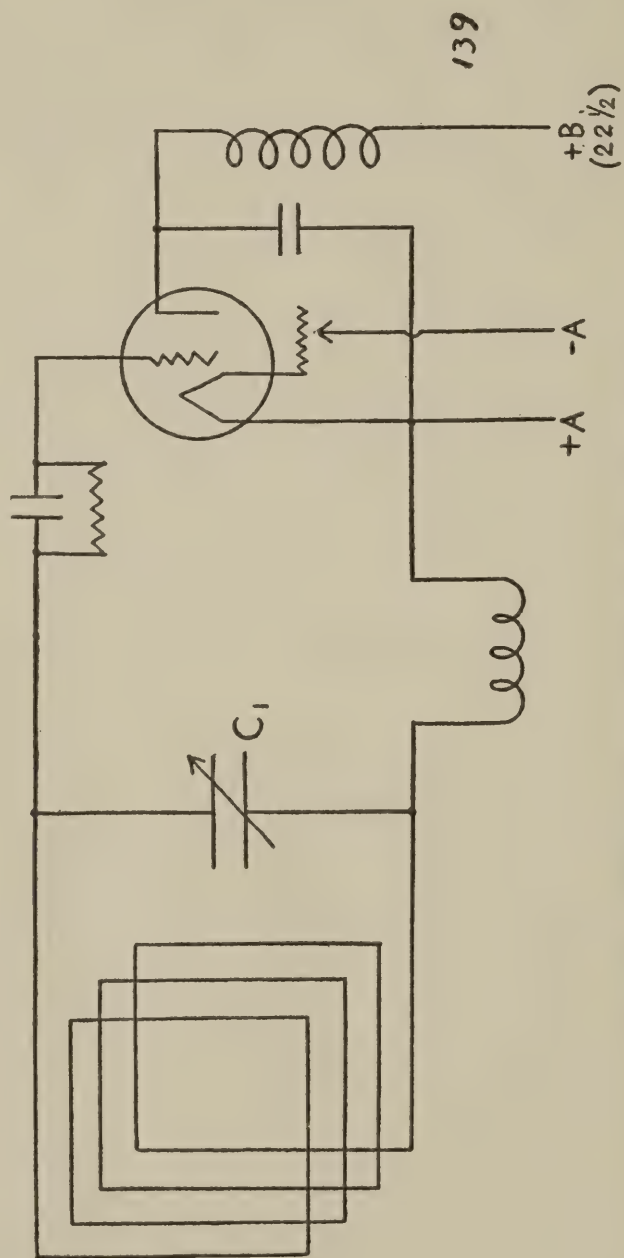


Fig. 139. Standard Loop, Pick-up Coil, and First Detector

a choke or a resistance at this point in the B battery lead. It is, however, a highly desirable refinement where the same B battery is used to supply the other tubes of the set. The condenser C_b is fixed and may have any value down to about .005 mcf., but should preferably be larger, say, .1 mcf.

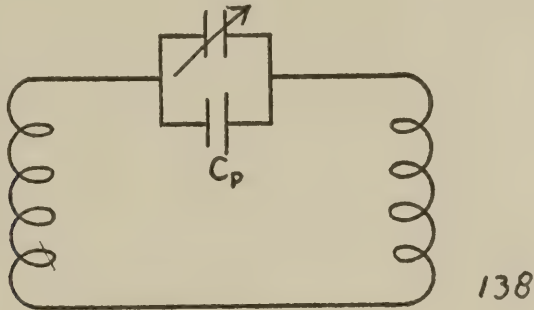


Fig. 138. *The Tuned Circuit of the Hartley Oscillator*

Loops. It is customary to employ a vertical loop instead of an antenna when using a superheterodyne. A square loop about eighteen inches on each side will require about fourteen turns of wire when used in connection with a .0005 mcf. tuning condenser. These turns should be spaced from $\frac{1}{4}$ to $\frac{1}{2}$ inch apart.

Use of a Pick-Up Coil. Coupling between the detector with the loop input and the oscillator is usually brought about by placing a small coil in the grid return of the detector and placing this coil so as to obtain magnetic coupling with one of the coils of the oscillator. Figure 139 shows a simple detector connected to a loop. The pick-up coil ordinarily has only six or eight turns of wire on a rather small tube, say $1\frac{5}{8}$ inches in diameter. It is to be noted in this simple detector circuit that the output circuit contains the primary of a transformer which is shunted by a condenser. This condenser may serve the double purpose of tuning the primary of this transformer and of permitting the high frequency currents to have a low impedance path back to the filament as must be the case in any good detector circuit.

Occasionally one sees a circuit in which coupling between the oscillator and first detector is brought about by means of a pick-up

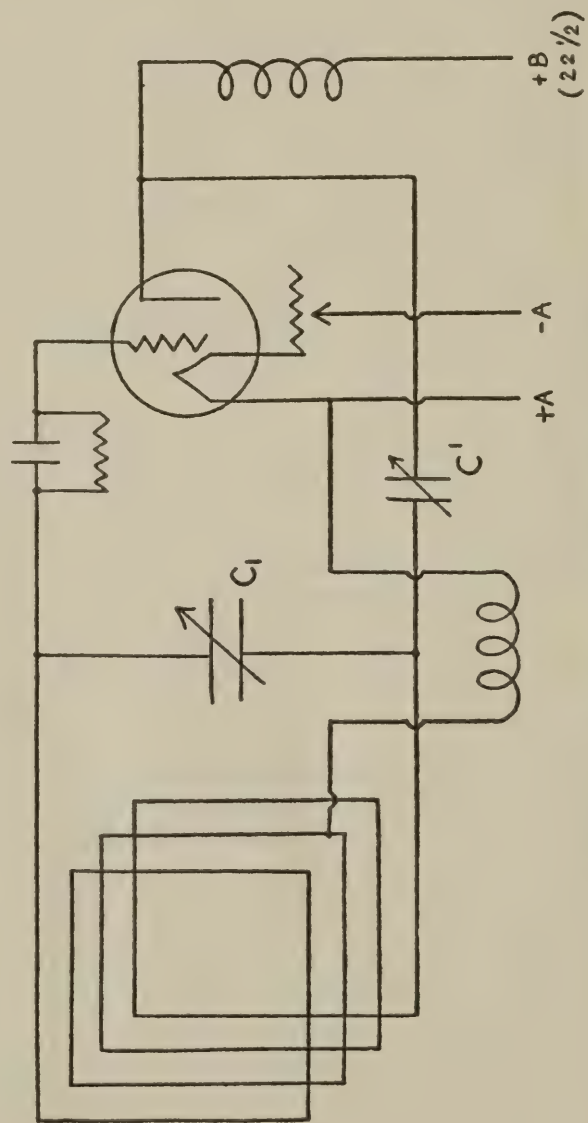


Fig. 140. A Regenerative First Detector. C' controls the Regeneration

coil in the plate circuit of the detector instead of the grid circuit. Beyond providing something "different" from the standard placement of this coil it is difficult to see what is gained thereby. When the pick-up coil is in the plate circuit, the first tube, which is supposed to be the detector, acts merely as a radio frequency amplifier and the plate circuit of this tube carries both the original signal frequency and the local oscillator frequency. These two high frequencies are then fed rather inefficiently through the intermediate frequency transformer which is not designed for such high frequencies and finally reach the first tube in the intermediate frequency amplifier still as separate high frequencies. Due to the imperfections of this tube as an amplifier (that is, its non-linear grid potential-plate current curve), this tube acts as a not very efficient detector and passes the intermediate or beat note frequency on to the rest of the amplifier. It would seem that the standard placement of the pick-up coil in the input circuit of the detector tube would be superior, since detection of the beat frequency would then take place in the detector tube instead of in the first tube of the intermediate frequency amplifier.

Many constructors do not use a grid leak and grid condenser in the first detector, but depend on the curvature of the grid potential-plate current curve of the tube. This method of detection was discussed at length in the section on tubes in Chapter V. Either form of detection gives reasonably satisfactory service.

Regenerative Detector. Figure 140 shows a detector circuit in which regeneration has been obtained by attaching a midpoint on the loop to the filament and connecting the other end through a condenser C' to the plate of the tube. If C' be made large we will have a circuit essentially like the "Hartley" oscillator of Figure 137. If C' be a midget variable condenser we will have a means of restricting the tendency of the set to oscillate and we will be able to control the amount of regeneration.

Some writers recommend that a small fixed condenser, about .0002 mcf., be used for C' and that the grid return on the loop be connected at various points other than the center until a point is found which permits of regeneration but not oscillation. This

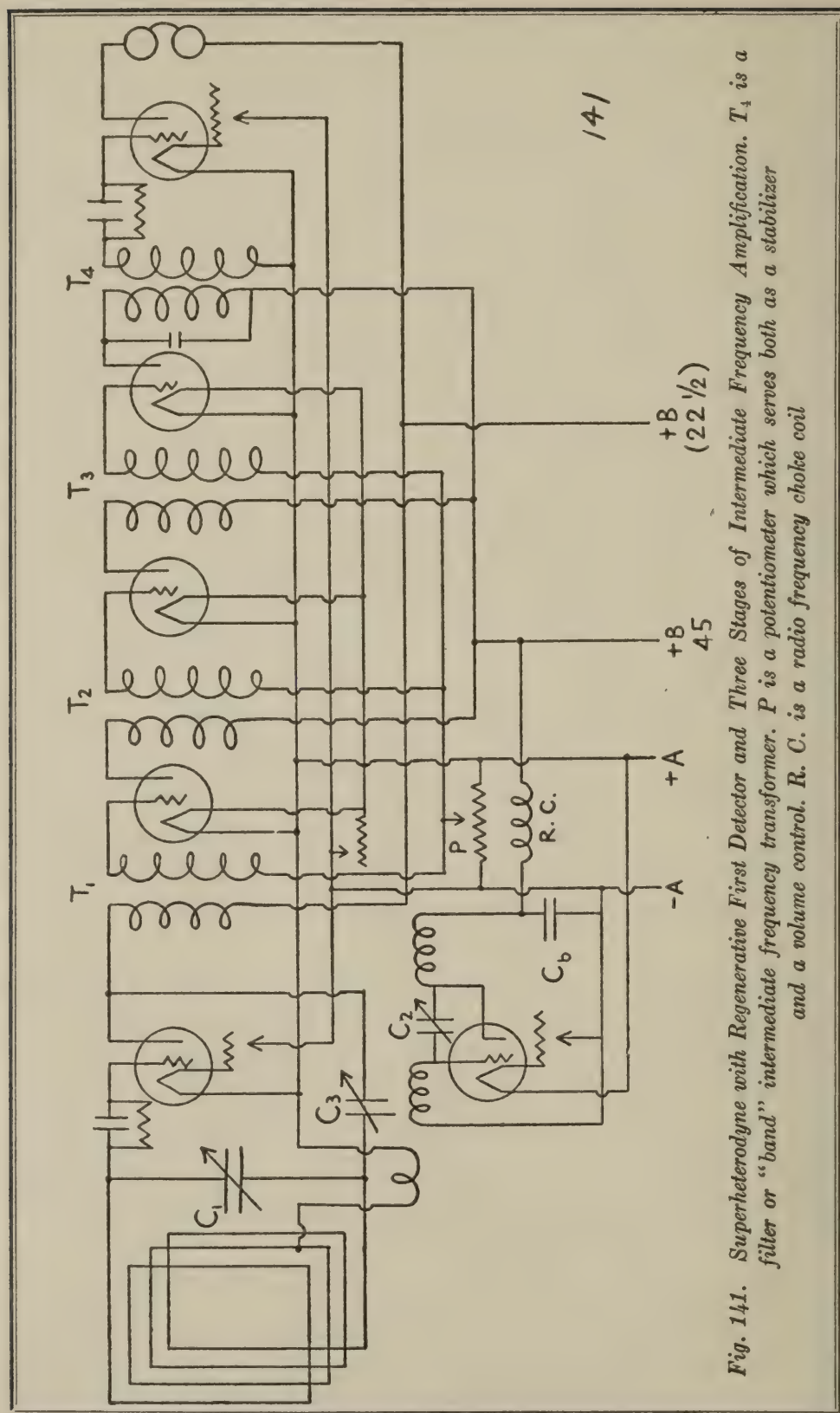


Fig. 141. Superheterodyne with Regenerative First Detector and Three Stages of Intermediate Frequency Amplification. T_1 is a filter or "band" intermediate frequency transformer. P is a potentiometer which serves both as a stabilizer and a volume control. $R.C.$ is a radio frequency choke coil

method does, of course, reduce the controls of the set by one, but it does not permit of any control of the regeneration when one uses the set.

When making the set regenerative by the use of a condenser as just described it is advisable to use a transformer after the detector tube which does not have a condenser across its primary, for such a condenser would bi-pass the high frequency currents which should be flowing back into the loop.

A Superheterodyne Circuit. Figure 141 gives the wiring diagram of a superheterodyne employing a Hartley oscillator, a regenerative first detector, three stages of amplification for the beat frequency commonly called "intermediate frequency" and a simple second detector. It is assumed that any type of audio amplification desired will be added for loud speaker operation.

It might appear at first hand that such a set is complicated to operate, but such is not the case. There are only two tuning controls in addition to the regenerative control and the potentiometer stabilizer. Either or both of these latter adjustments serve as much needed volume controls on this type of receiver, although volume control can also be obtained by a separate rheostat in the filament of one of the tubes of the intermediate frequency amplifier. The two principal controls, and the only ones needed for changing from station to station, are the two large condensers, one on the loop C_1 , the other on the oscillator C_2 . The intermediate frequency transformers although more or less of the partially tuned type do not require attention since they are all adjusted for the same intermediate frequency and left that way.

Use of the Potentiometer. Although the tendency of this intermediate frequency amplifier to develop self-sustained oscillations is not so great as that of a high frequency amplifier, the tendency is great enough to make necessary the use of some form of stabilizing device. The most commonly used device is the simple potentiometer as shown in Figure 141. It

is, of course, possible to apply any of the bridge balancing devices of the two preceding chapters, but the fact that the inductances here involved are much larger than those in high frequency transformers makes some of these methods rather impracticable.

Intermediate Frequency Transformers. All of the intermediate frequency transformers are built to give maximum amplification over a few thousand cycles in the vicinity of 50,000 and to give extremely poor transfer of energy at other frequencies. At least one of the transformers must act as a band filter in this manner. Since the number of turns of wire on both the primary and secondary is ordinarily quite large, the distributed capacity will be large and the transformer as a whole will have a not very sharply defined resonant frequency. This fact permits it to act as a band filter. All of the transformers used in any one receiver must have their resonant regions at exactly the same place on the frequency scale. Ordinarily this region of maximum transfer is not sharply enough defined and one of the transformers is made with less turns of wire and is tuned with an external fixed condenser. Such a transformer is commonly called a filter. It may be used as the first or last transformer, or in fact in any other position. There is a slight advantage in using it just before the second detector, since in that position it can act as a filter against tube disturbances that may have developed in the set up to that point.

Some intermediate frequency transformers are built very much after the manner of tuned radio frequency transformers, except that more wire is used and the condensers are fixed. This type is very efficient, but if not properly constructed will tune too sharply. There is the danger of not passing a band of frequencies sufficiently wide to take care of the higher notes in music. In fact the compromise between intermediate frequency transformers that tune sharply enough to keep out stray signals of audio frequency and permit of easy separation of stations and those that tune so sharply as to clip the sidebands badly is the goal sought by every manufacturer of these transformers. Not all, by any means, of these transformers are made to amplify at a frequency of 50,000. Many iron core ones have been made to work as low as 30,000 peak value,

and some air core transformers work in the neighborhood of 100,000. One of the references at the end of this chapter gives the details of a superheterodyne whose intermediate frequency transformers are simply tuned radio frequency transformers working at about 500,000 and employing Hazeltine neutralization.

Loss Stabilized Intermediate Frequency Transformer. One of the most popular intermediate frequency transformers on the present market (1926) is of the tuned radio frequency type. Losses are introduced in the transformer to serve the double purpose of broadening the resonant frequency band and to provide stabilization. Losses are introduced in two ways, first by using small wire (about No. 36 enameled) and by wrapping it at random in a groove about $\frac{1}{8}$ inch in width and $1\frac{3}{4}$ inches in diameter so that the distributed capacity is high, and second, by introducing inductive losses by the simple process of putting a flat piece of metal close to the end of the secondary. The amount of metal in this position is variable so that the transformer may be adjusted in the factory for the proper amount of loss. A small condenser is also fastened across the end of the secondary and doubtless absorbs some energy from the secondary, although its principal purpose is to tune that coil. In spite of the fact that this transformer is self-stabilizing, it is usually used with a potentiometer as shown in the standard diagram of Figure 141. The potentiometer stabilizes the set still more and provides an additional volume control. These transformers pass a narrow enough band of frequencies so that no special filter transformer need be used.

It is hardly practicable to build intermediate frequency transformers in the home laboratory unless one has facilities usually found only in research laboratories.

Combined Oscillator and Detector. It may have occurred to the reader that separate tubes for the first detector and the oscillator are not strictly necessary. The only serious difficulty with having these two functions performed with fair efficiency by a single tube lies in keeping the tuning of the oscillator and that of the loop independent. A rather ingenious

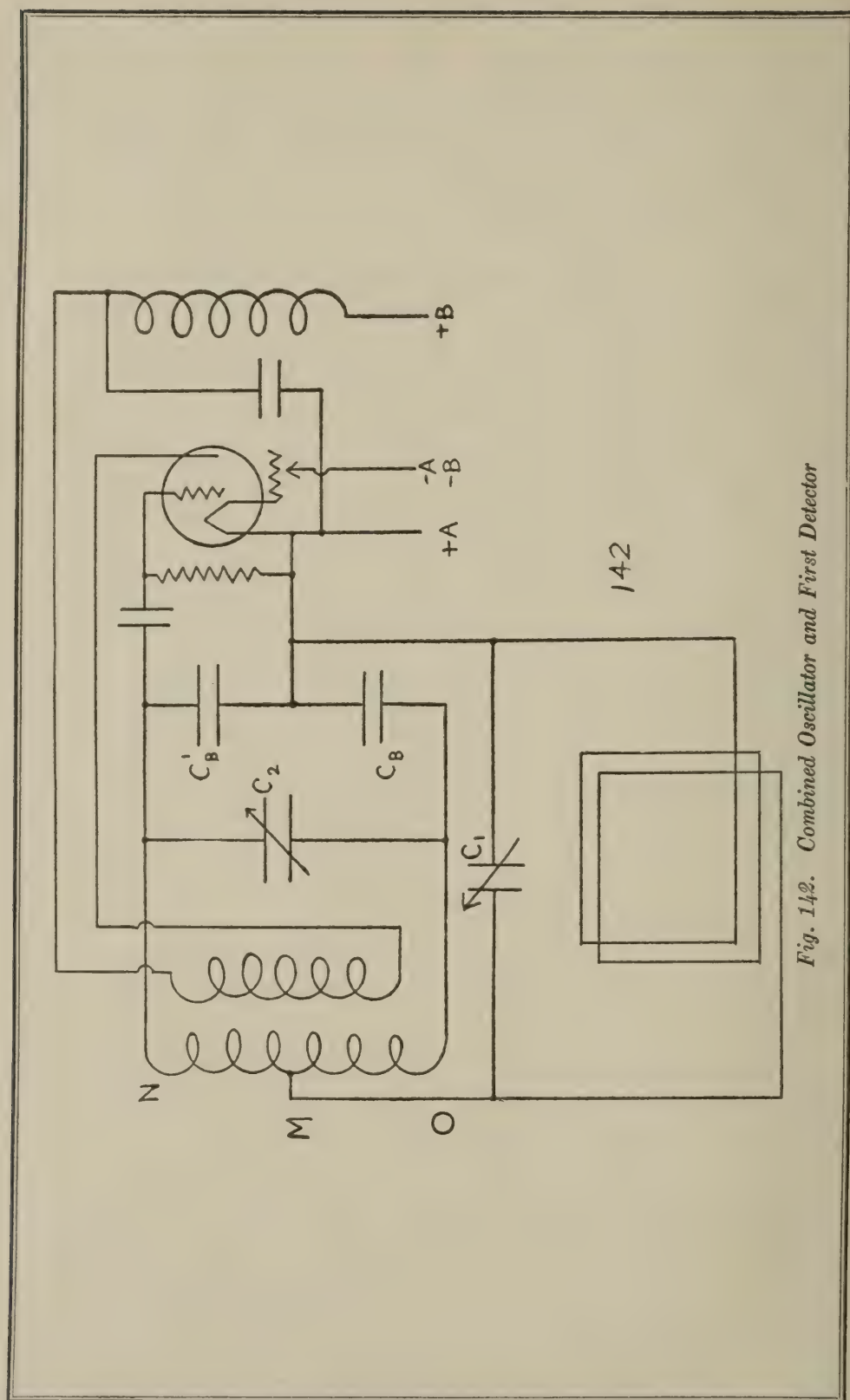


Fig. 142. Combined Oscillator and First Detector

scheme for accomplishing this purpose is shown in Figure 142. It is called the "Pressley" combined oscillator and first detector. If the two condensers C_b are equal and if M is the midpoint of the coil ON , or if we have the condition

$$\frac{C_b}{C'_b} = \frac{MN}{MO}$$

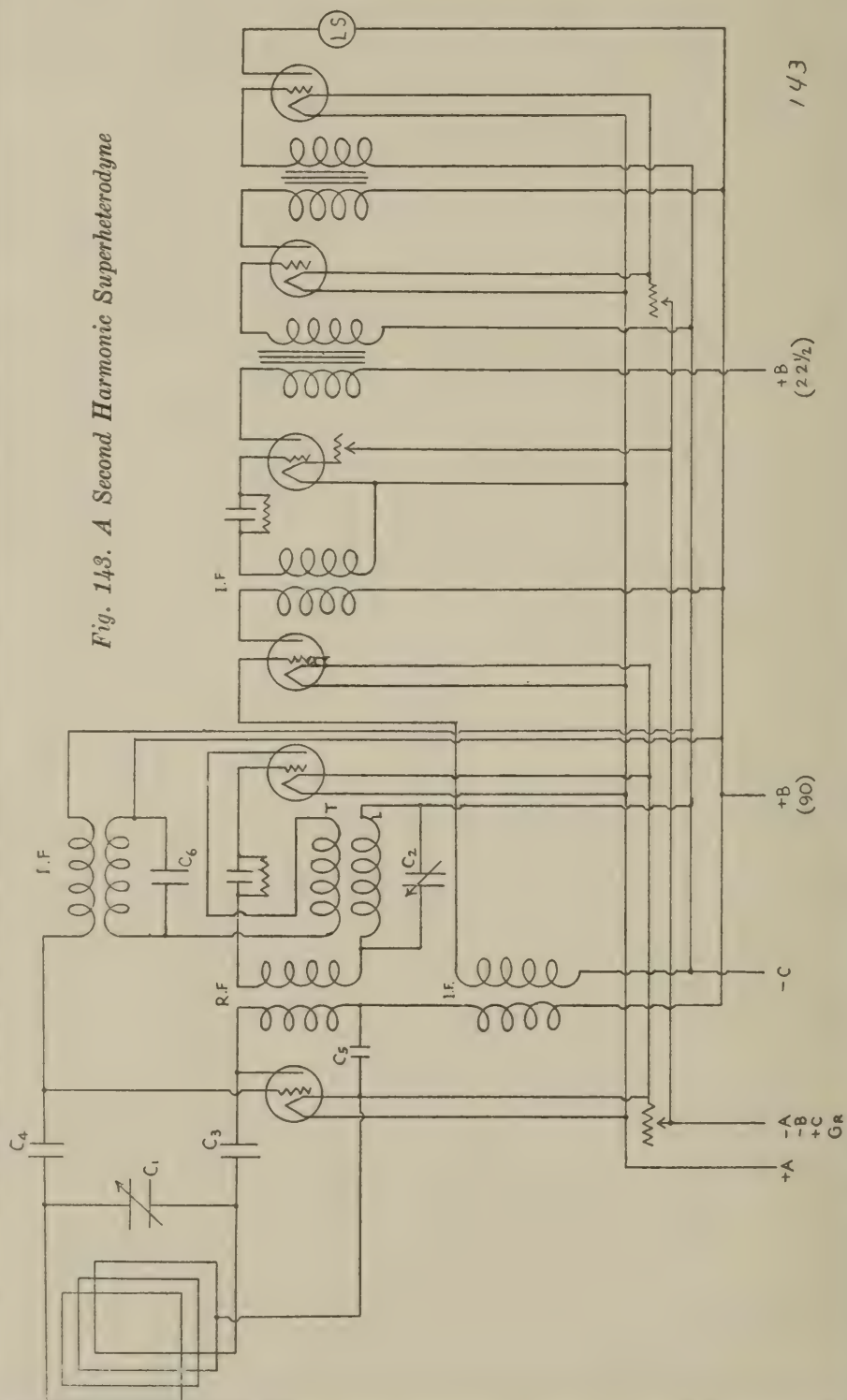
where MN and MO are the inductances of the respective sections of the coil ON , then the tuning of the loop and of the oscillator will be independent, for the circuit OM, MN, C'_b and C_b form a balanced alternating current bridge. C'_b and C_b must be made quite small since they add to the minimum capacity of the tuned circuit of the oscillator. Some models of this receiver have been made with C'_b and C_b as variable condensers mounted on the same shaft so that they serve as the tuning condenser of the oscillator and at the same time keep the ratio

$$\frac{C_b}{C'_b}$$

constant although the individual values of these condensers change as the set is tuned from one station to another.

Second Harmonic Oscillators. Another possible variation in superheterodyne construction depends on the fact that an oscillating tube seldom gives a pure frequency. Usually several multiples of this fundamental frequency are present. If the tuned coils of the oscillator are built to have four times the inductance of an oscillator built for a frequency of 1,000,000 then with the same setting of the condenser the oscillator with the larger coils will have a fundamental frequency (called a first harmonic) of 500,000 and a second harmonic of 1,000,000. This second harmonic will not be nearly as strong as the first harmonic, but will be entirely adequate for beat reception with the desired radio signal. In fact having the strong first harmonic so much farther removed from the frequency of the signal to which the loop is tuned is considered an advantage. The writer is rather skeptical as to the advantages claimed for the use of a second

Fig. 143. A Second Harmonic Superheterodyne



harmonic when the rest of the circuit is the same as that ordinarily used with the fundamental of the oscillator.

The use of the second harmonic of the oscillator has been worked into some rather more complicated superheterodyne circuits, one of which is shown in Figure 143. A single tube is here used both as oscillator and first detector. The two tuned circuits are kept separate by using one stage of untuned radio frequency amplification ahead of the detector; but some reliance for the stability of the circuit is based on the fact that by using the second harmonic of the oscillator the oscillator itself is tuned to a frequency far away from that to which the loop is tuned. No pick-up coil is needed since the secondary of the untuned radio frequency transformer is made to feed into the grid circuit of the oscillating tube.

The plate circuit of the oscillator-detector tube carries the primary of an intermediate frequency filter transformer the secondary of which feeds back to the grid of the first tube, thus making the first tube do double duty as a radio frequency and an intermediate frequency amplifier. The plate circuit of this tube, of course, must carry an intermediate frequency transformer primary shunted by a condenser in order that it may work efficiently as a radio frequency as well as an intermediate frequency amplifier.

The third tube acts as a straight intermediate frequency amplifier, the fourth tube as a detector and the last two tubes are in transformer coupled stages of audio amplification.

Regeneration to the loop is provided through a small variable condenser C_3 in the manner already described for the standard type of superheterodyne. If there is too much inherent tendency to oscillate, Rice neutralization may be obtained by making C_3 sufficiently small.

Tuned Radio Frequency with a Superheterodyne. Many amateurs, in seeking for new worlds to conquer, wish to combine ordinary tuned radio frequency with the superheterodyne. Figure 144 shows one stage of tuned radio frequency with an antenna for a source. If it is desired to use a loop, the loop would be substituted for the coil S_1 . This stage of amplification is neutralized by the Hazeltine method

employing the neutralizing coil wrapped with the primary. The coil S_2 takes the place of the loop in the circuit diagram of Figure 141. A superheterodyne should never be used in con-

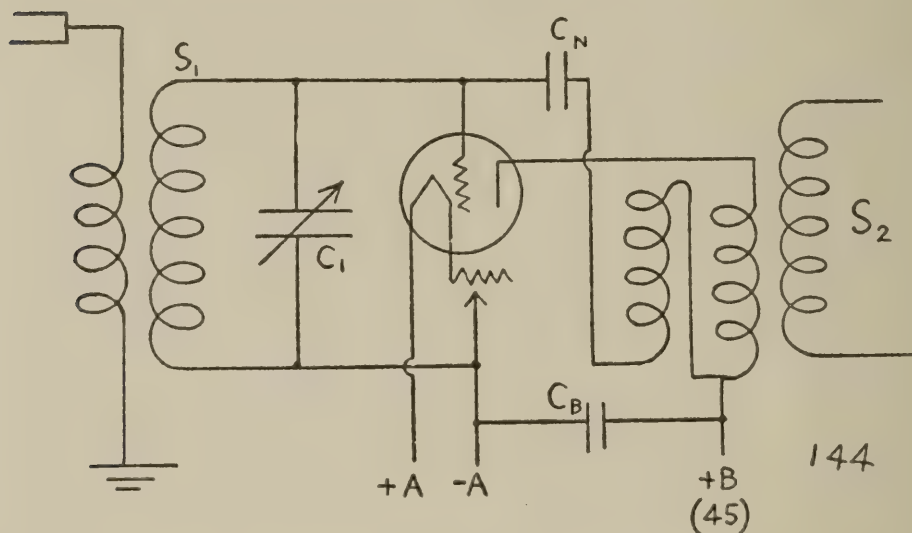


Fig. 144. One Stage of Balanced Tuned Radio Frequency Amplification for a Superheterodyne. Coil S_2 is connected in place of the loop

nection with an antenna unless a properly balanced radio frequency stage comes between the antenna circuit and the rest of the superheterodyne. Otherwise there is great danger of energy from the oscillator finding its way into the antenna. Such a use of a superheterodyne may be a greater menace to the good of radio reception than the much condemned simple regenerative receivers.

Superheterodynes vs. Tuned Radio Frequency Receivers. One may well ask what in particular the superheterodyne offers that is not to be had with tuned radio frequency receivers. It is a little difficult to answer this question one way or another. A short time ago one might have said that it offered greater portability since it operated from a loop. The loop also adds somewhat to its ability to separate stations. But now we have multi-stage tuned radio frequency receivers also operating from loops. Also the simplicity of tuning

(only two controls) of the superheterodyne is to be found on many of the new models of tuned radio frequency receivers where gang control on the tuning condensers is now the vogue, there being sometimes two and sometimes only one control for all the condensers. It is very doubtful if intermediate frequency transformers can be made as selective as tuned radio frequency transformers without clipping the side bands more than the latter do. The quality of many superheterodynes is notably lacking in brilliance due to the inferior amplification of the edges of the side bands in the intermediate frequency amplifier. In general it may be expected that a superheterodyne operating on a loop will give about the same results that a good two stage tuned radio frequency receiver operating from a fairly good antenna will give.

There is really little point in attempting to operate a superheterodyne from an antenna, for a good two stage tuned radio frequency receiver will amplify signals from the antenna to the point where the noise level becomes objectionable. It is true that the voltage amplification of a well made superheterodyne is superior to that of a two stage tuned radio frequency receiver. (Otherwise it would not be able to do with the feeble signals from a loop what the other set accomplishes only with the aid of the relatively strong signals from the antenna). But there is no object in the amplification of any signal which is not large in comparison to the ever-present stray disturbances to which we refer as the noise level.

Combination Circuits. The reader has already been introduced to the idea of combining separate ideas in receiver design in the same set in the superheterodyne to which regeneration was added and again in the suggestion for combining balanced tuned radio frequency with this type of receiver. It will therefore not be difficult to conceive of a receiver employing tuned radio frequency amplification with a regenerative detector. Two such circuits have become popular under the names of the Roberts and the Browning-Drake. These circuits are essentially similar except for the peculiar winding of the primary of the radio frequency transformer in the Browning-Drake referred to in Chapter VII. The Roberts uses the jointly wound coil system of primary

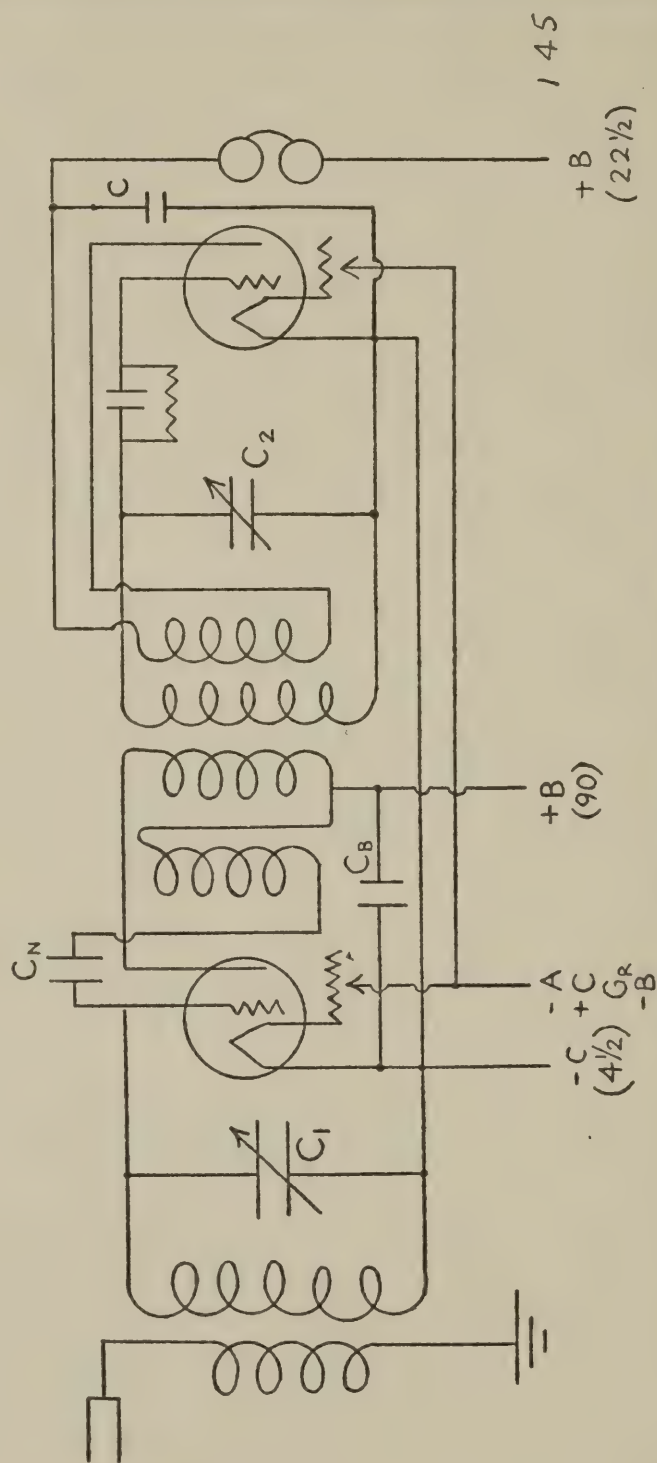


Fig. 145. The "Roberts" Circuit without Reflexing

and neutralizing coil to stabilize the set, while most of the Brown-ing-Drake type use the older Hazeltine method of neutralization where the neutralizing condenser is attached to the secondary.

Usually only one stage of tuned radio frequency is employed, and this stage, with the regenerative detector, is nearly equal to two stages of ordinary tuned radio frequency with a simple detector—equal both in selectivity and volume. Production of this type of receiver is quite restricted by the patent situation, for the owners of the patents on regeneration are not the owners of the methods of neutralizing that seem most desirable for this receiver.

“ Roberts ” Circuit. Figure 145 gives the circuit diagram of the so-called “ Roberts ” circuit with a single stage of balanced tuned radio frequency and a regenerative detector. Any type of audio amplifier may be added. The balanced first tube serves effectively as a block to keep the set from radiating from the antenna when the regenerative detector is permitted to oscillate.

We have already seen that it is possible to make a single tube do double duty, as in the case of the special superheterodyne where the functions of oscillator and detector were performed by one tube, and in the case of the second harmonic superheterodyne where the first tube acted both as a radio and intermediate frequency amplifier.

It is also possible to have a single tube act both as a radio frequency and an audio frequency amplifier. The original “ Roberts ” circuit was so arranged.

“ Harkness ” Reflex. A very simple receiver of this latter type known as the Harkness one-tube reflex is shown in Figure 146. The first tube is in the first place a radio frequency amplifier. It feeds into a tuned transformer $L_3 L_4 C_2$ where the primary L_3 consists of about fifteen turns of wire wrapped on top of the secondary with only fabric cloth between for insulation. The tuned secondary feeds the high frequency e. m. f. s across a crystal detector whose circuit carries also the primary of an audio

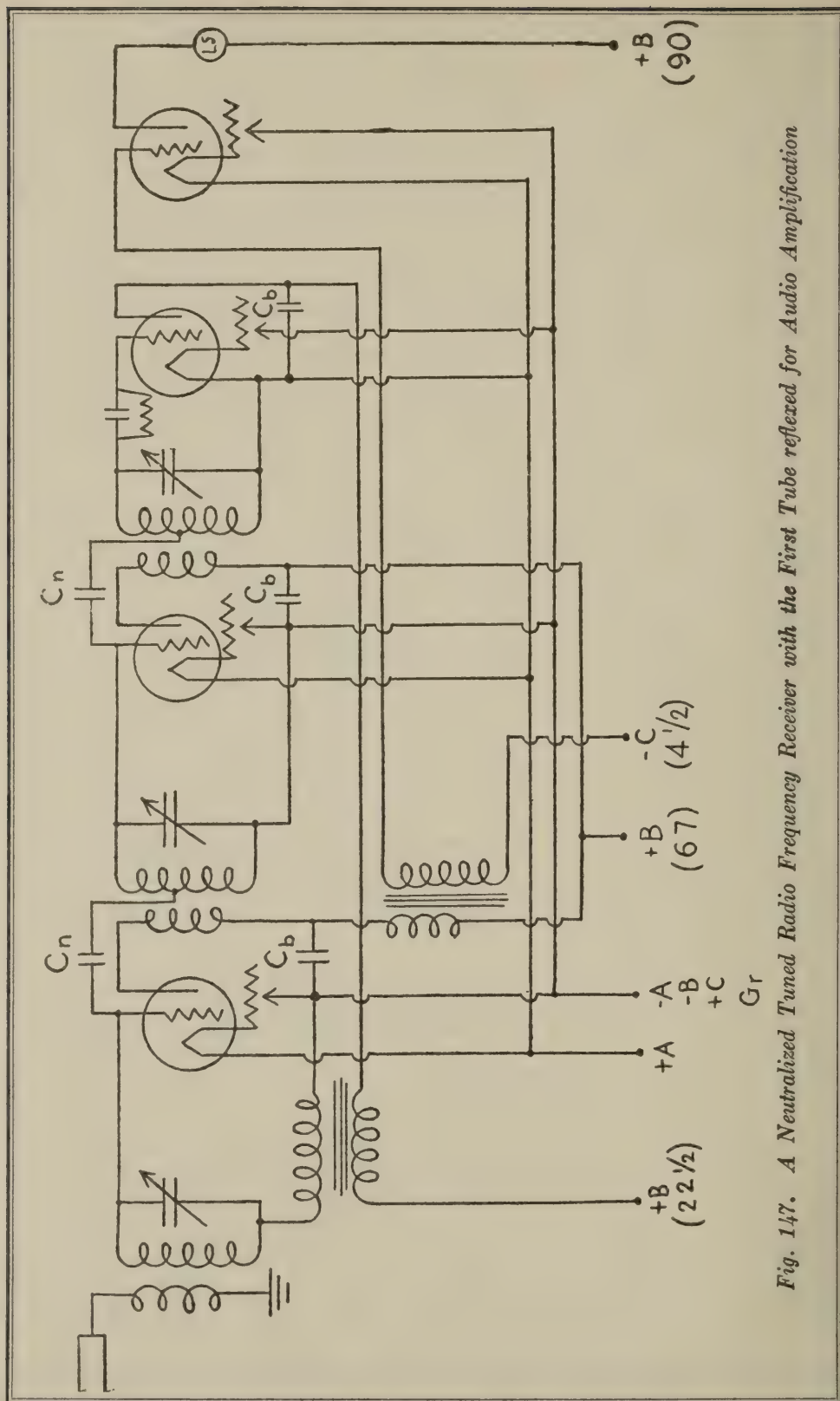


Fig. 147. A Neutralized Tuned Radio Frequency Receiver with the First Tube reflexed for Audio Amplification

frequency transformer. The secondary of this transformer feeds the input circuit of the tube in the manner shown in the diagram, so that the tube now acts as an audio frequency amplifier. The tube is not very apt to oscillate because of the absorption of the aperiodic antenna circuit on the input and the closely coupled

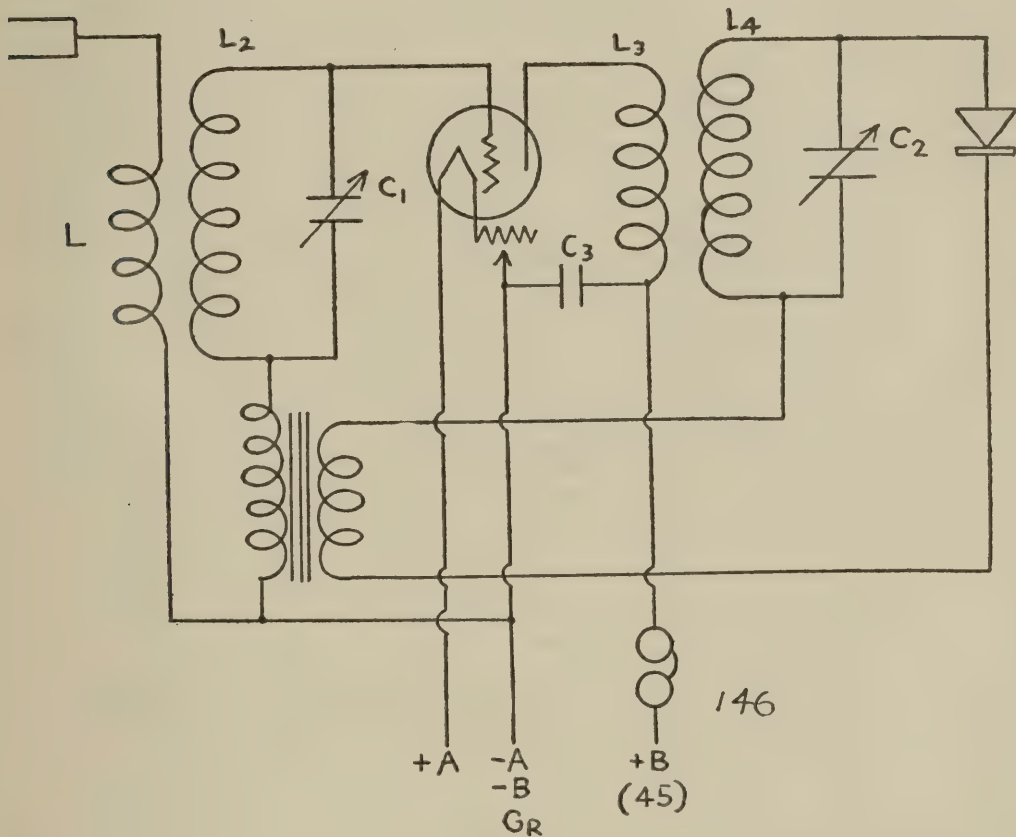


Fig. 146. "Harkness" Reflex Circuit

crystal detector on the output. This circuit is recommended to people who wish a very simple and at the same time a very successful set and who are public spirited enough to desire not to increase the number of regenerative receivers in existence.

A Reflexed Neutrodyne. Another reflexed set is shown in Figure 147, where we find a neutralized radio frequency amplifier of two stages, a detector, one stage of audio frequency

amplification reflexed back through the first radio frequency amplifier and a final stage of straight audio amplification.

Declining Popularity of the Reflexed Receiver.

The only object in employing the reflex principle is to reduce the number of tubes employed for accomplishing a given result. It is now quite generally conceded that while the overall amplification of a reflexed set is greater than would be obtained with the same number of tubes without reflexing, still one tube, when used both as a radio and an audio frequency amplifier will not serve either function as efficiently as when used for only one of these purposes. It also seems likely that the audio e. m. f. s impressed on the input of a radio frequency amplifier tube have a slight modulating effect on the high frequency currents and thereby produce a small amount of distortion. At all events, the lowering of the price of good tubes, and the more general use of storage batteries seems to have gone hand in hand with the swing of public favor from reflexed to straight model receivers.

Chapter IX—References

Superheterodynes

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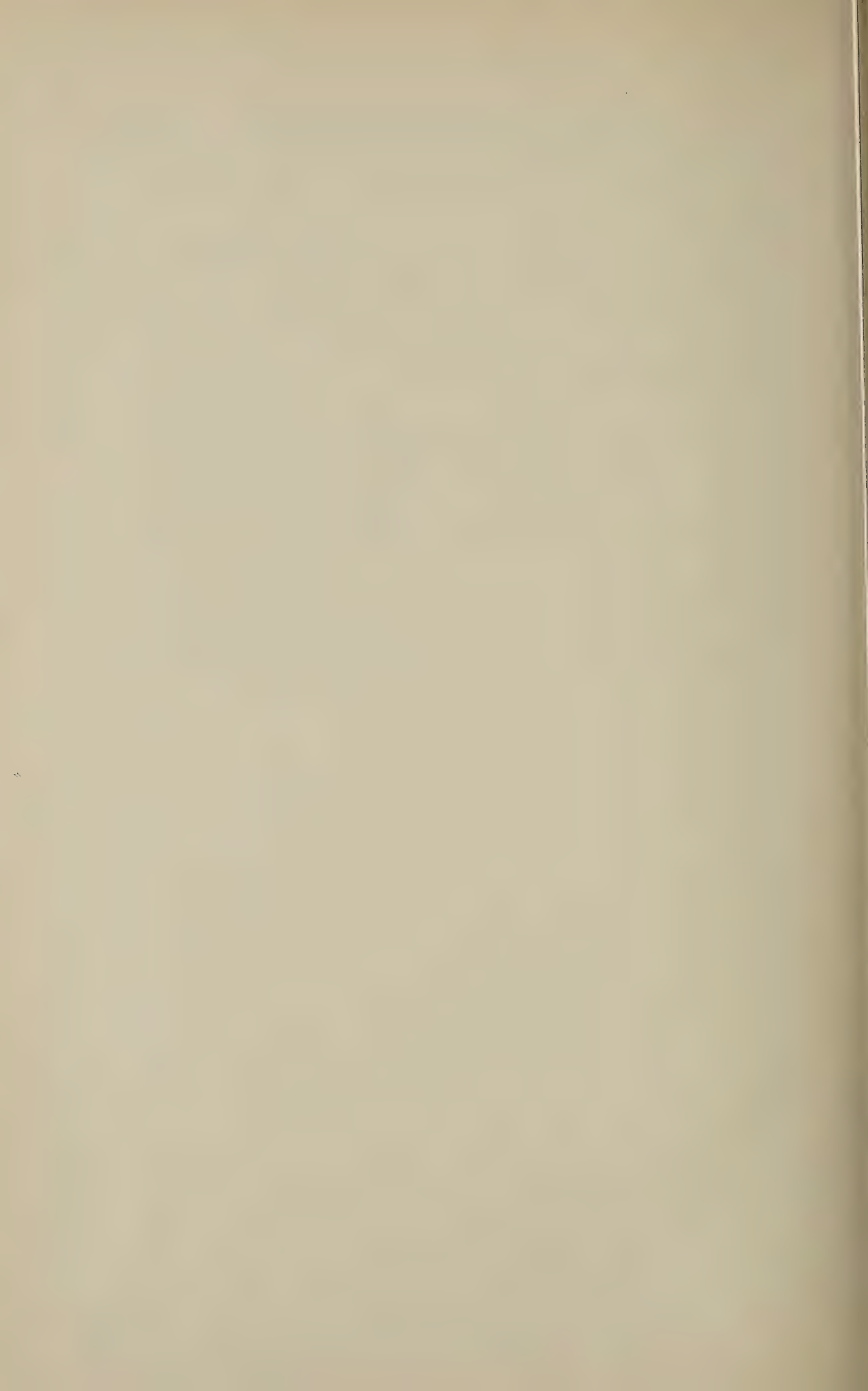
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**BATTERY CHARGERS AND BATTERY
ELIMINATORS**

TOPICAL INDEX

CHAPTER X

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CHAPTER X

Battery Chargers and Battery Eliminators

Necessity for Rectification. Nearly all residences are supplied with alternating instead of direct current. Such current is unsuitable for charging batteries, and must be rectified for such purposes. For charging batteries it is not necessary to have a steady source of direct current, but all of the current must flow in one direction. All rectifying devices distort the wave form of the alternating current, and in Figure 148 we have all of the pulses of e. m. f. in one direction indicated by the light curved lines and the actual current as passed by a rectifier

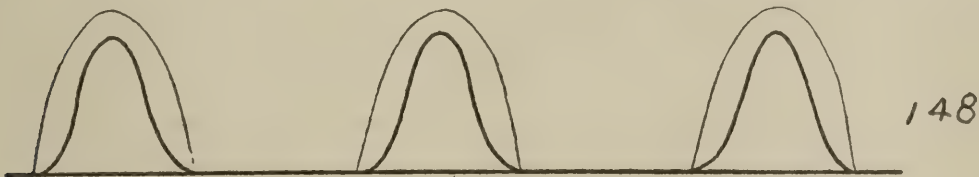


Fig. 148. The sine curve in light lines indicates the half cycles of alternating current. The dark line indicates the actual rectified current

indicated by the heavy lines. Of course the shape of the rectified current varies greatly with different types of rectifiers.

A device producing pulses of the type shown in Figure 148 is called a single wave rectifier. It merely stops the flow of current in one direction. It is possible to combine two of these rectifiers in such a way as to supply the output line with the other half of the alternating current inverted. Such current would appear somewhat like the heavy line in Figure 149. A rectifier of the latter type is somewhat more efficient if we rate efficiency as the ratio between the alternating current power supplied to the device

and the direct current power delivered. Since, however, the total amount of power consumed in radio receiving devices is small in terms of the power that we use for ordinary lighting purposes in a house, we are concerned more with the low cost of the installation, and the convenience of the apparatus, than with the efficiency. It is therefore quite common to use single wave rectification for small battery chargers. The other type of rectifier is commonly called a *full* or *double* wave rectifier.

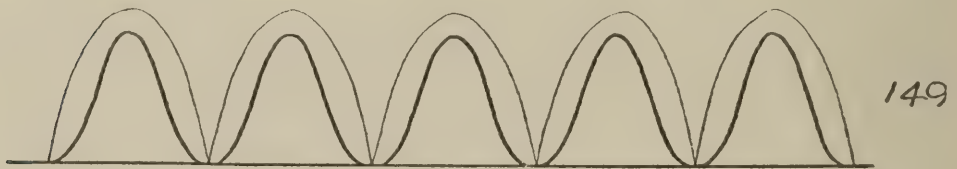


Fig. 149. The heavy line indicates the current from a double wave rectifier

Vibrating Rectifier. One of the most common methods employed for the rectification of alternating current is the so-called vibrating rectifier. Its name is descriptive. A small armature vibrates to and fro in synchronism with the alternating current in such a way as to make contact with the output line only when the flow of current is in the proper direction. The method is successful enough for purposes of rectification, but is likely to permit of sparking at the time of breaking the contact, and so, unless properly shielded, it may be a source of much noise in neighboring receivers. These vibrating rectifiers are frequently made to give full wave rectification.

Chemical Rectification. Perhaps the most commonly used rectifier in home built outfits depends on the uni-lateral conductivity between certain chemical solutions and certain metals. Ordinarily a jar is filled with a water solution of the chemicals to be used and two electrodes are inserted in the solution. The metals in most common use are lead and aluminum. Most of the earlier home constructors used a concentrated solution of ordinary borax for the electrolyte. Sodium phosphate and ammonium phosphate have also been used quite extensively. All of the above

chemicals operate well enough as rectifiers in connection with the lead and aluminum electrodes; but the life of the rectifier is likely to be short. Several commercial companies have put out secret combinations of chemicals to be used in this type of rectifier, and most of these combinations are more satisfactory than solutions made up from the simple chemicals. Of course many other combinations of metals and chemical solutions are possible, but the lead and aluminum with the combination of chemicals now sold for the purpose is the chemical rectifier in most common use.

Thermal Emission. We have already seen in our study of tubes that a three-electrode tube is essentially a rectifier, for the hot filament emits electrons which can travel toward the grid and plate when they are positive, but neither grid nor plate can supply electrons for current in the opposite direction. When a three-electrode tube is used as a rectifier, the grid is fastened to the plate to prevent it from acquiring a negative potential and so restricting the flow of electrons to the plate. Tubes are manufactured especially for rectification purposes and these do not contain a grid. They are called two-electrode tubes and are known by the trade name, kenotron.

Ionization Rectifiers. If we take an evacuated tube similar to the kenotrons just described and partially fill it with a gas which is chemically inert but which ionizes easily we can increase the current capacity of the tube. As before, the hot filament emits electrons which will be attracted to the plate when the plate is positive. These electrons in motion ionize the gas and greatly increase its conductivity. When the polarity of the plate and hot filament is reversed no electrons can leave the cold plate and hence no current will flow in this direction. This is the principle employed in the tungar rectifier.

Another rectifier which has attracted wide attention during the last year is a tube depending on the ionization of gas but in which no hot filament is required. The unilateral conductivity of the tube is obtained by making the electrodes of different shapes.

So far these tubes have been made only in very small current capacities—too small for use in battery charging outfits. They are, however, adequate for supplying power to the plate circuits of sets and because of their simplicity and economy in operation (no filament current) and long life they have already achieved widespread public favor as rectifiers in B battery eliminators.

Battery Charging Outfits. It is hardly feasible to make battery chargers of large current capacity in the home laboratory. At least there are many good chargers on the market at prices that make it seem more economical to buy than to build. Many of these chargers are arranged to supply a low potential large current source for charging A batteries and a high potential low current line for charging B batteries. If, however, one desires a charger for charging at low rates, less than one ampere, it is entirely practicable to assemble the apparatus, and perhaps to make most of it.

Charging Directly from an A. C. Line. For this type of charging (called trickle charging) chemical rectifiers are used almost exclusively. The arrangement of apparatus is simple and is shown in Figure 150. The lamp is an ordinary tungsten lamp serving as a resistance to limit the flow of current. The fuse is not strictly necessary but is advisable especially if such a

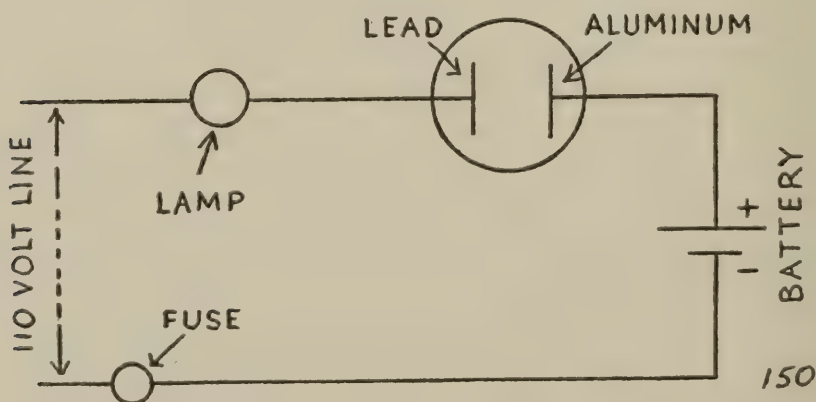


Fig. 150. A simple Battery Charging Circuit connected directly to the 110-volt Line

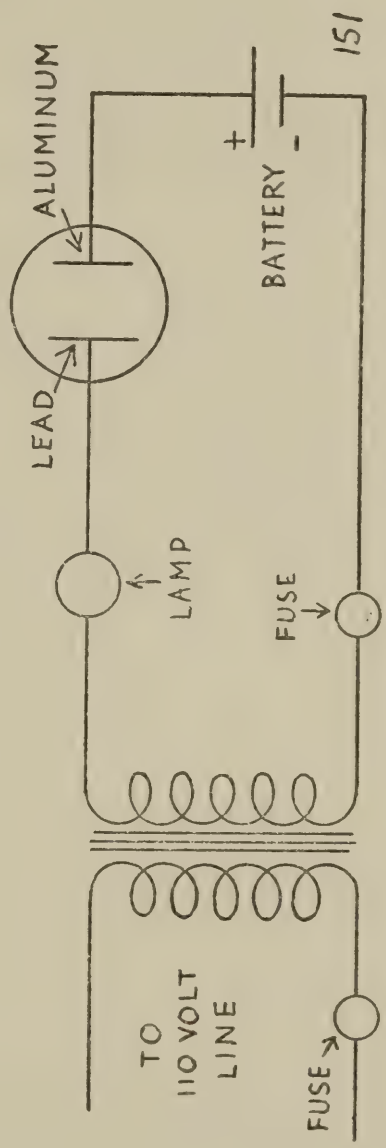


Fig. 151. A Battery Charger connected to the Line through a Transformer

simple arrangement is used in order to protect the line from possible short circuit. This charger employs a single electrolytic rectifier which may be either built up or purchased complete. The battery to be charged may be anything from a 2-volt single cell for peanut tubes up to a 48-volt B battery block. For charging A batteries a lamp of from 60 to 100 watts would be used, while for the B batteries a smaller lamp would be used, from 60 to 25 watts, depending on the rate at which one wishes to charge. Obviously the lower the watt rating of the lamp, the greater is its resistance to the flow of current.

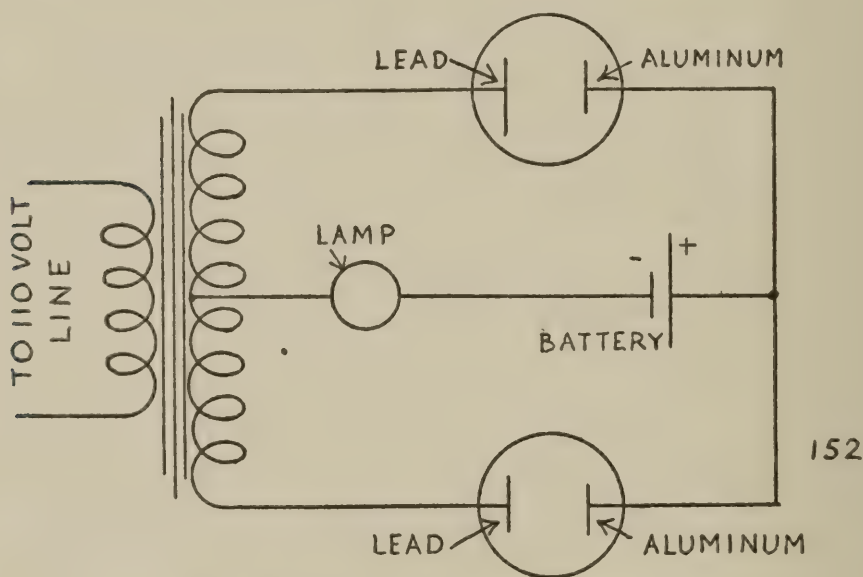


Fig. 152. A Two Wave Chemical Rectifier

Use of a Transformer. Charging directly from the line as shown in Figure 150 is not approved of by fire underwriters, and the circuit of Figure 151 is the one which should be used to meet with their approval. If A batteries only are to be charged the transformer shown in this figure may be made with less turns in its secondary than in its primary in order to step down the voltage of the line. This method would represent economy, but actually the cost of operating one of these chargers is negligibly small in any case.

Both of the chargers just described are single wave rectifiers. If a transformer with a mid-tap from its secondary be used, it

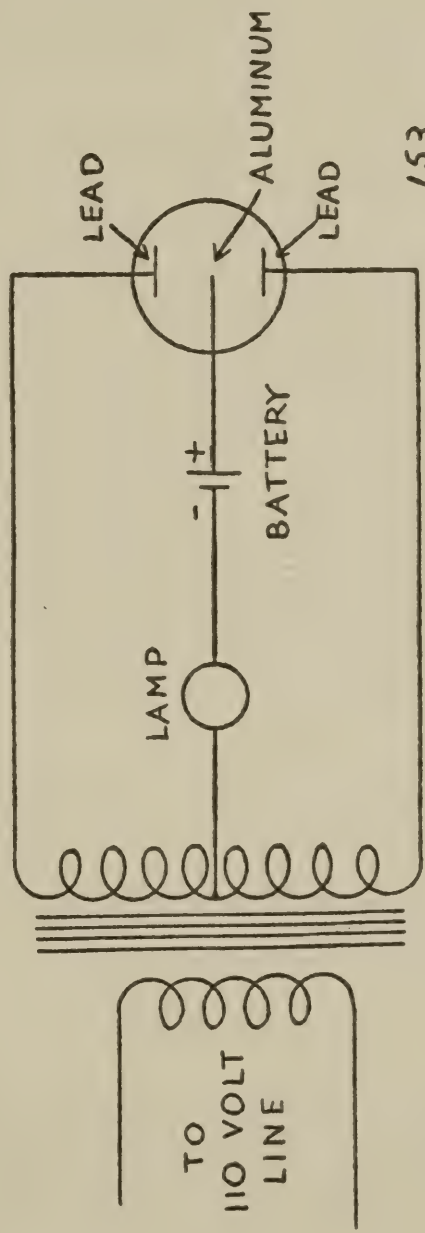


Fig. 153. A Two Wave Charger employing a Single Rectifier with three Electrodes

is possible to use two chemical rectifiers and obtain both waves. This is seldom done on trickle chargers, but since the method is quite common in B battery eliminators it is shown here in Figure 152 as a battery charger. Of course this charger will charge at approximately twice the rate of the single wave rectifiers just described. A single rectifier jar may be used in this arrangement as shown in Figure 153 by the simple process of placing two lead and one aluminum electrodes in the same jar.

Transformers. Although the principle of the transformer has been covered in the early part of this book and its use in amplifying circuits has been discussed at some length, we have up to this point not been obliged to consider seriously its functions in a power circuit. When current flows in one direction through the primary windings of a transformer all the iron of the transformer core becomes magnetized. When the current is reversed the iron passes through zero magnetization and finally becomes magnetized in the opposite direction to that of the magnetization of its original state. This process of being magnetized, first in one direction and then in the other, occurs in every complete cycle of the alternating current. It is shown in texts on magnetism that the energy stored in every unit volume of the core of a transformer is given by

$$W = \frac{B^2}{8\pi\mu}$$

where B is the magnetic induction and μ the permeability and π has the value of 3.14. If we know the total volume of the iron core and the permeability of the type of iron (or steel) in the core, and also the amount of magnetic induction, we can figure the amount of energy that can be stored in the core on one-half of a cycle. If we also know the frequency of the alternating current we can compute the amount of energy that is stored (and removed from) the core per second. Since the power delivered by the secondary is transferred from the primary to the secondary through

the medium of the core, we see that the power taken from the secondary can not exceed the amount of energy that we have found the core can handle per second. On the other hand, if we know the amount of power we wish to take from the secondary, we can calculate the size of core necessary to handle this amount of energy per second.

From the foregoing discussion it is apparent that for the handling of a given amount of power, a transformer with a much larger core would be required if the current alternated only 25 times per second than if it alternated 60 times. For in the first case energy can be transferred only 50 times per second, and in the second case it can be transferred 120 times. Hence in the first case more energy must be transferred on each half cycle if the same amount is to be handled as in the case of the 60 cycle transformer. The increase in core is not exactly in the inverse ratio of the frequency because greater magnetization without unduly overheating the core is possible at low frequencies. But roughly speaking the inverse ratio of the frequencies forms a fair idea of the relative sizes of the cores of at least the smaller transformers such as are required in battery chargers and B battery eliminators.

Construction of Transformers. All transformers of this type are built up in laminations. Sheet iron may be used, but soft silicon steel seems to be in greatest favor now as core material. The thickness of the laminations depends on the frequency of current to be used. For 25 cycle a thickness of 18 mils is satisfactory, but for 60 cycle it should be 15 or less. Naturally, the thinner laminations are entirely satisfactory for the lower frequency also. The simplest way to build up the core in the home laboratory is the rectangular style illustrated in Figure 154. For a small battery charger, the area of cross section of the core might have about 2 square inches instead of 1 square inch as in the core of Figure 154. The rectangle might be about $6 \times 4\frac{1}{2}$ inches outside dimensions instead of the dimensions shown in Figure 154. The primary would have between seven hundred and one thousand turns of wire of about No. 20 or No. 22 enameled copper. If the secondary were to be used for A batteries only,

it would carry about one third to one half the number of turns used on the primary, while if it were intended for B battery charging as well it would carry the same number of turns as the primary.

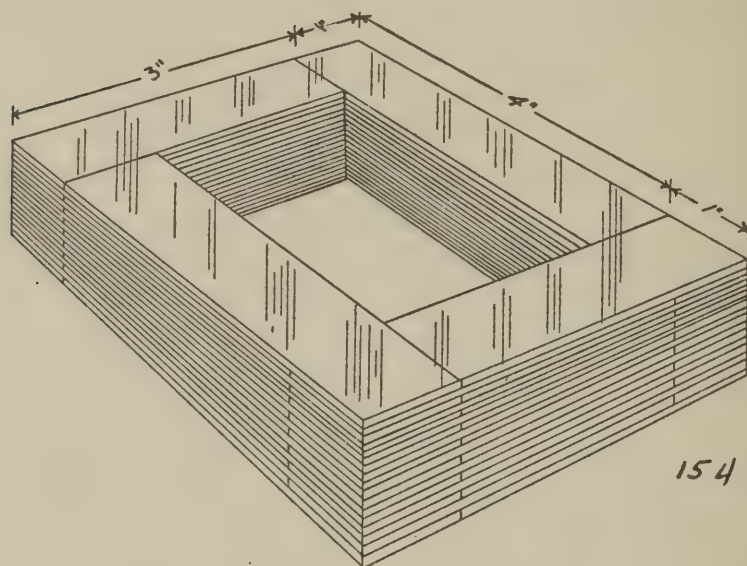


Fig. 154. A Transformer Core built of straight pieces of Silicon Steel. The pieces are 1 by 3 inches and 1 by 4 inches as shown and the joints at the corners are alternated with every layer

If the transformer were to be used in the circuit of Figure 152 each section of the secondary would contain the number of turns ordinarily placed on a simple secondary.

When transformers are designed for use in B battery eliminators they are required to supply small current (.05 amperes or less) at fairly high potentials. Since the advent of the new power tubes, many of these transformers are made to supply 350 volts or more from their secondaries. Ordinarily 100 volts or more of this original high value will be lost in the various parts of the eliminator so that not much more than 200 volts will be delivered to the set. Most of the present popular literature on the subject of B battery eliminators describes sets whose transformers are wound to supply about 275 volts. These eliminators supply from 125 to 150 volts to the radio receiver.

The cores of the transformers for these eliminators have a cross sectional area of about one square inch, and the outside dimensions of the core are about 5 by 4 inches. (See Figure 154). Both primary and secondary are usually wrapped around one of the longer legs, although occasionally half of each is wrapped around each of the two longer legs. The average primary in a transformer of this kind has about 1,000 turns, and each section of the secondary 2,500 turns. The primary should be about No. 26 or 28 enameled copper wire and the secondary about No. 28 or 30. Practically all of the popular radio magazines of the last year (1926) have carried reasonably authentic information on the manufacture of these small transformers. It is to be remembered, however, that nearly all of these popular articles have described transformers for use with 60 cycle current. A transformer of the dimensions given above has some margin of output, for the amount of energy required from a B battery eliminator is small. Hence, it is possible to take a transformer of this size and use it for 25 cycle; but the method is a makeshift one and the best results can not be expected unless the size of the core be increased as has been pointed out.

In the construction of power transformers one is concerned not only with the transfer of energy, but also with the loss from the power line when no current is being drawn from the secondary. To reduce the current taken from the line when the secondary is idle, large power transformers are wound with more turns on the primary for low frequency current than for high. But in a B battery eliminator the line is ordinarily shut off when the secondary is not in use, and in any case, efficiency is not extremely important. So in constructing a transformer with a larger core for 25 cycle current, it is hardly necessary to increase the primary turns beyond the 1,000 recommended for the 60 cycle transformer. Actually both the 60 and 25 cycle transformer when used for a B battery eliminator would be more efficient with more turns in the primary. But such a procedure would make necessary an increase of turns in the secondary, and the expense and trouble would hardly be justifiable.

Choke Coils. We have already considered choke coils as being large inductances which may be used to permit the flow of steady current but restrict the flow of alternating or pulsating currents. For use with currents of commercial frequencies, these choke coils are made very much like transformers, except that only one winding is used. If the amount of direct current to be passed is large, there is some danger of the core becoming magnetically saturated. When the core is in this condition the inductance of the choke coil is greatly reduced. Saturation can be prevented, unless very large direct currents are used, by having a break in the core. The break may be small. It may be obtained by taking a hack saw and cutting a slot all the way through the core after it is finished.

Size of Wire in Transformers and Choke Coils.

In the commercial manufacture of small transformers and choke coils there is a great tendency to save money by using small wire in the coils. It must be remembered, however, that there is a great deal of difference in the resistance of the wire of a choke coil containing about 5,000 turns if the wire be No. 32 instead of No. 28. It must also be remembered that when direct current flows through the choke there will be a potential drop across its terminals equal to

$$P.D. = IR$$

Now, if I is the current supplied to the plate circuits of a receiving set it is obvious that when I changes (due to moving a potentiometer or due to change in the strength of signals in the audio amplifier) the potential drop across the coil will change. This means that the plate current supply will be irregular, for obviously the potential wasted across the choke coil must be deducted from the original amount. It follows that this source of irregularity should be reduced to the extent possible, and the way to do this is to increase the size of wire in the choke coil and also in both the primary and secondary of the transformer.

Of course, much of the e. m. f. available across the terminals of the secondary is used up across the rectifying element itself,

and in general, the amount so used increases with the amount of current passing through. As we have seen, the amount of e. m. f. used up in overcoming potential drops in the various coils is also increased with increasing current. So it follows that the more current we draw, the less the available e.m.f. for use on the radio receiver. In other words, the direct e. m. f. supplied to a large radio receiver will be less than that supplied by the same device to a small one. This feature is one of the objectionable characteristics of the B battery eliminator as compared to B batteries. The obvious way to improve B battery eliminators is to improve the rectifying devices and to reduce the resistance of other parts of the circuit to a minimum.

B Battery Eliminator Circuit. Even with full wave rectification, a very irregular current is obtained from a rectifying device as shown in Figure 149 at the beginning of this chapter. Since very steady current must be supplied to the plate circuits of a receiving set, it is necessary to pass the pulsating current of the rectifier through a circuit which will smooth it out. Such a current is called a filter.

If we were to connect a large condenser across the lines carrying the pulsating current we could think of the condenser as a reservoir for electricity. The pulses would keep adding electricity to the condenser and so keep it charged. The charged condenser would then act as a reservoir to provide somewhat steadier current for the line. The line, of course, should offer some resistance to the flow of the current so as to make the pulses flow principally into the condenser instead of passing into the line. This is the function served by a choke coil. In actual practice better results are obtained by using several condensers and choke coils properly arranged than by the use of just one choke and one condenser unless this one choke and condenser be impracticably large.

Figure 155 shows an arrangement now in common and successful use as a B battery eliminator. The transformer is made with three taps so that by turning a multi-pole switch a greater or less number of turns may be included in the primary. In this manner the e. m. f. developed across the secondary may be conveniently

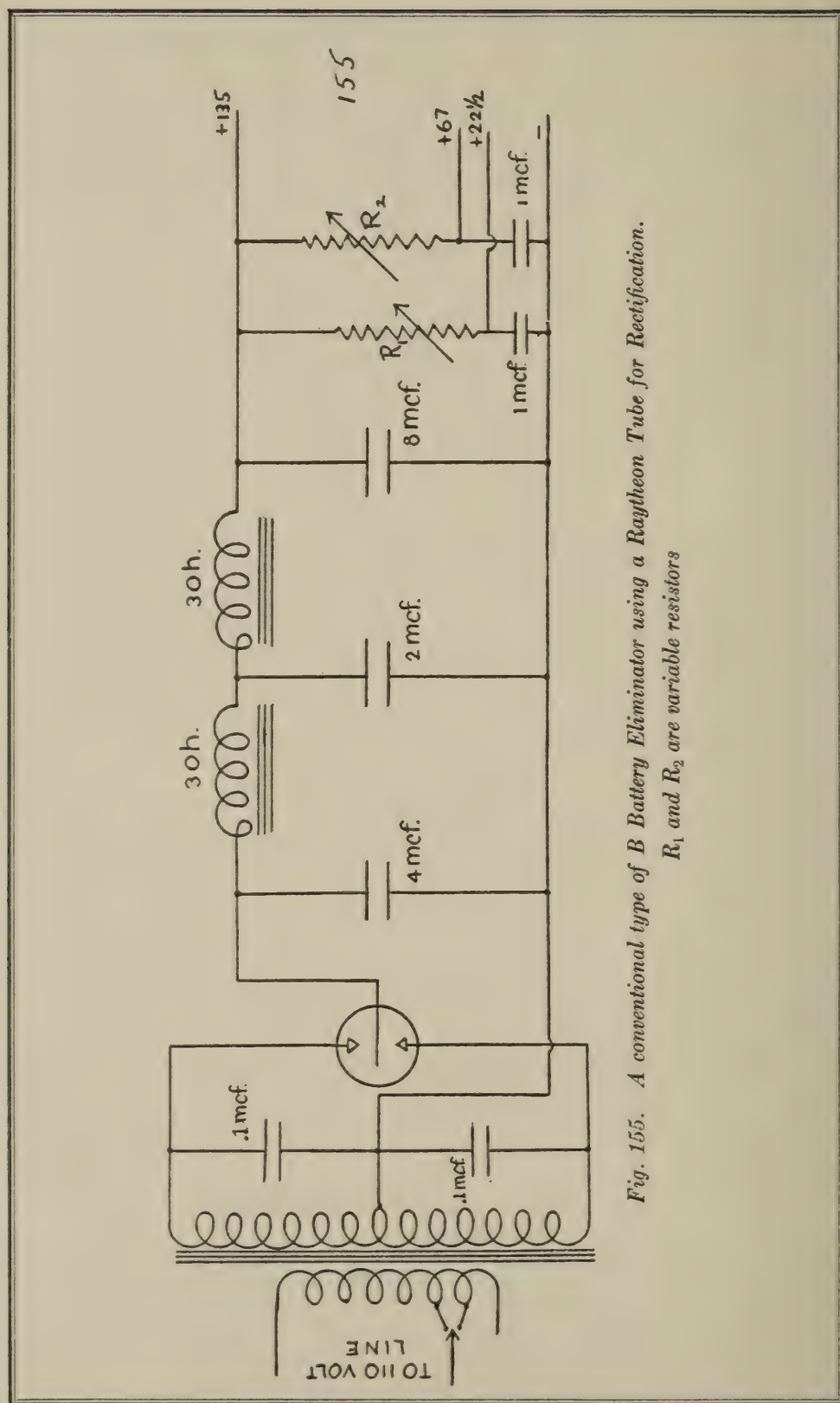


Fig. 155. A conventional type of B Battery Eliminator using a Raytheon Tube for Rectification.

R_1 and R_2 are variable resistors

controlled for loads of different size. Reducing the primary turns of course increases the secondary e. m. f. The secondary is of the double type for providing double wave rectification. The rectifier is a "Raytheon" tube, an ionization rectifier without a heated filament.

The arrangement of choke coils and condensers in the filter circuit is indicated in the diagram. Low voltage taps are arranged in the output of the eliminator for detector and radio frequency amplifier circuits by the use of variable resistors of large value.

This eliminator as shown is for use with 60 cycle current. It may be used for 25 cycle current by simply increasing the three filter condensers to about double the value here given provided not more than 25 to 30 milliamperes of current are to be used. If more current is needed, the transformer should be constructed for 25 cycle current as suggested in a former paragraph and the choke coils should be increased both in size of core and in number of turns in addition to doubling the size of the filter condensers.

Eliminator and Chemical Rectifier. Figure 156 shows an eliminator circuit for use with a chemical rectifier. The only essential difference here (beyond the change in rectifiers) is in the method of obtaining the low voltage supply. A high resistance is connected directly across the output terminals and taps are taken off in potentiometer fashion. To make this method notably better than the variable resistor method of the preceding circuit, this whole resistor should have a relatively small value, about 5,000 ohms. Such a resistor would draw considerable current, perhaps 25 milliamperes. Since the chemical rectifier will handle much more current than the tube of the previous circuit, this potentiometer method is practical here but not in the former circuit.

Eliminator with Kenotrons. In Figure 157 we have the transformer and two kenotron tubes of a B battery eliminator. The filter circuit would be the same as that of Figure 155. It is to be noted that the transformer carries an additional secondary of a small number of turns which supplies the current

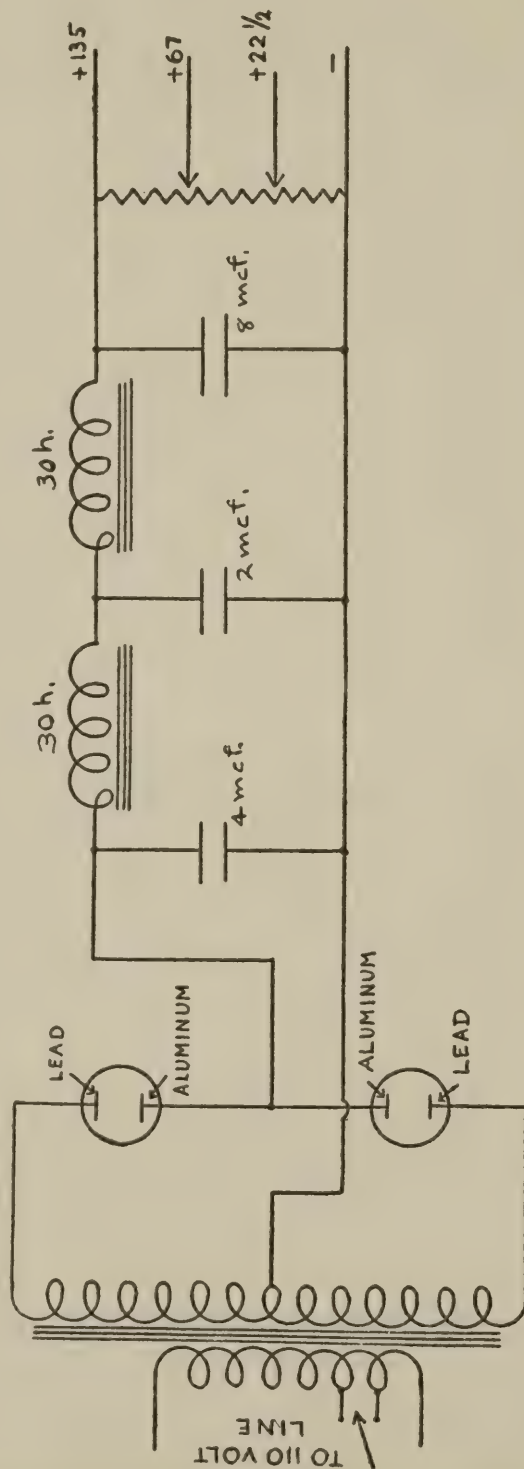


Fig. 156. *AB Eliminator using Chemical Rectification. The sizes of coils and condensers in the filter are the same as in those of the preceding figure*

for lighting the filaments of the kenotrons. Ordinary three-electrode tubes may be used instead of special tubes by simply fastening the grid and plate binding posts of the tube sockets together. The life of a tube designed for detecting and amplifying purposes is not likely to be as long, however, as that of a tube designed for use as a power rectifier.

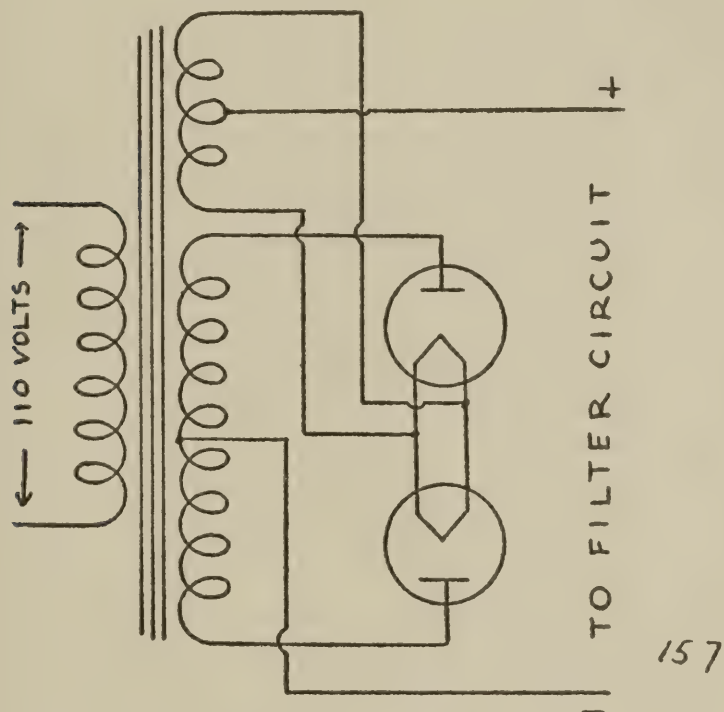


Fig. 157. A Two Wave Thermionic Rectifier

Kenotrons are also made with two filaments in the same tube, so that double wave rectification with a single tube is possible as in the case of the "Raytheon" tube of Figure 155.

Filament Current. We have already seen that the filament of a tube may be lighted from alternating current of proper voltage when used for rectifying purposes. The same method of lighting may be applied to the filaments of tubes in a radio receiver. When this method of lighting is used the grid returns can not be made to one end of the filament, for then the hum of the

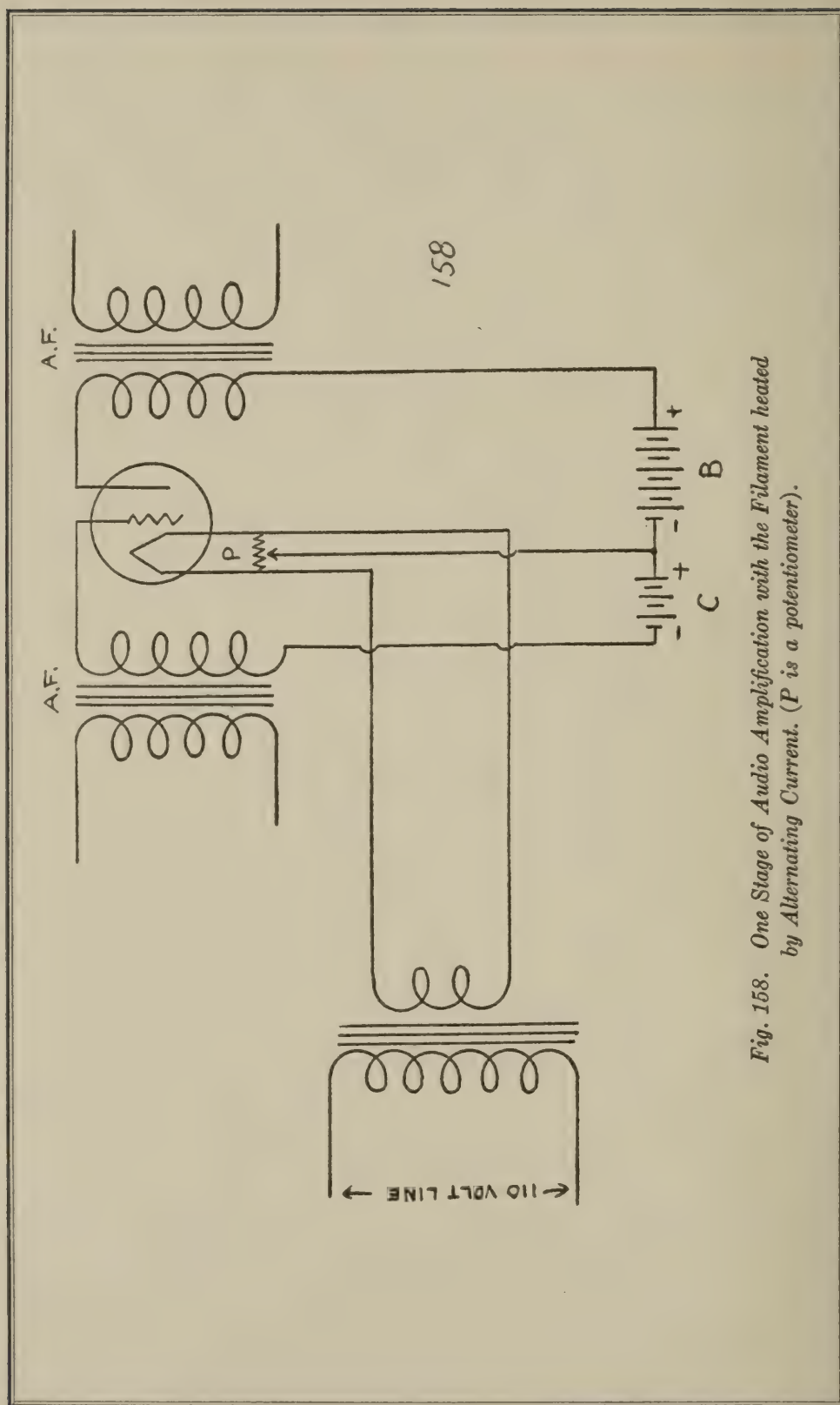


Fig. 158. One Stage of Audio Amplification with the Filament heated by Alternating Current. (P is a potentiometer).

alternating current would be introduced into the receiver. Theoretically the grid return, whether it be direct or through a C battery, should be made to the mid-point of the filament. Of course this procedure is not possible. But if a potentiometer be shunted across the filament, some point on the potentiometer can be found whose potential will always be that of the mid-point of the filament. The grid return is therefore connected to this point on the potentiometer.

In Figure 158 we see a simple circuit showing alternating filament supply to a single stage of audio frequency amplification. Note in particular the connections of the C battery in order that the "grid return" may be attached to the proper point to reduce hum in the receiver. Note also the manner in which the negative side of the B battery or B eliminator is connected to the circuit.

So far the application of alternating current to the filament of the detector tube has not been very successful. It appears to be too difficult to eliminate the hum of the low frequency current when used on a detector. The application of the method to the filaments of tubes in radio and intermediate frequency amplifiers is just beginning, and still offers plenty of opportunity for development. But alternating current supply for the filaments of audio amplifiers is already quite common, and as people realize the gain in quality from using real power amplifiers, the use of alternating current to supply the filaments of these larger tubes and the use of B battery eliminators to supply large plate currents will undoubtedly increase.

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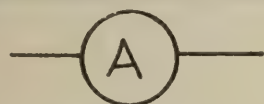
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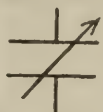
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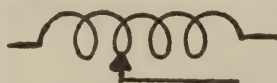
STANDARD GRAPHICAL SYMBOLS



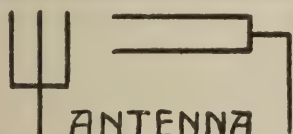
AMMETER



VARIABLE
CONDENSER

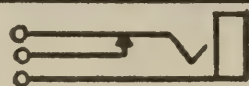
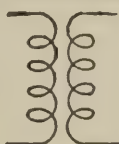


INDUCTOR
ADJUSTABLE

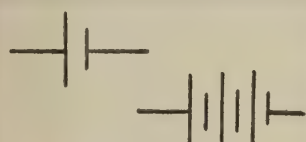


ANTENNA
OR AERIAL

COUPLER,
INDUCTIVE
MUTUAL
INDUCTOR



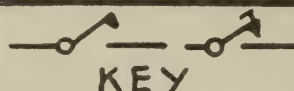
JACK, SINGLE



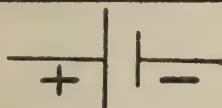
BATTERY



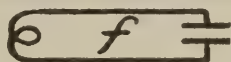
CRYSTAL
DETECTOR



KEY



BATTERY
POLARITY INDICATED



FREQUENCY
METER
WAVEMETER



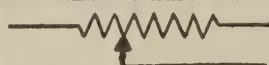
LIGHTNING
ARRESTER



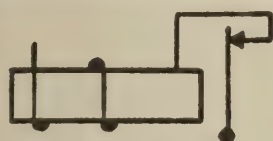
GALVANOMETER



RESISTOR



RESISTOR
VARIABLE



BUZZER



GROUND



INDUCTOR



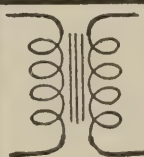
TELEPHONE
RECEIVER



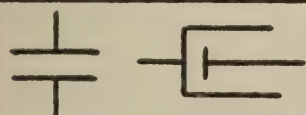
COIL ANTENNA



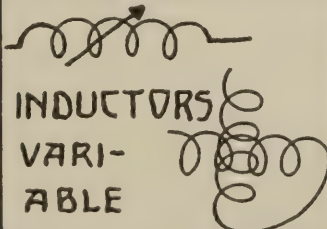
INDUCTOR
IRON CORE



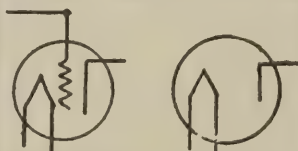
TRANS-
FORMER



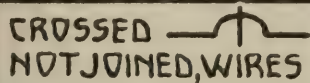
FIXED SHIELDED
CONDENSERS



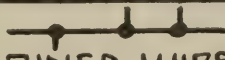
INDUCTORS
VARI-
ABLE



TRIODE DIODE
VACUUM TUBES



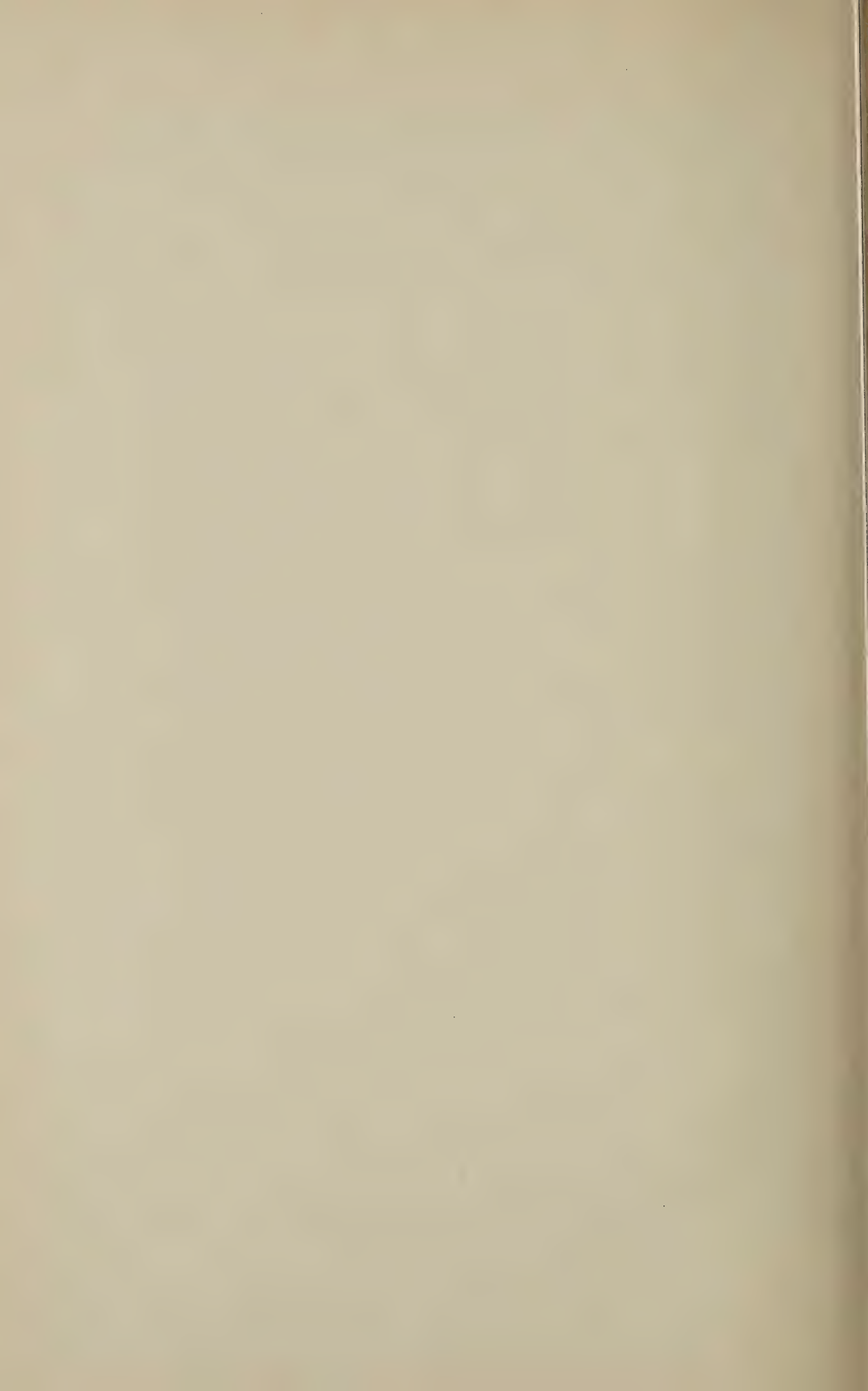
CROSSED
NOT JOINED, WIRES



JOINED, WIRES



VOLTMETER



Glossary of Terms

A

“ A ” Battery. Battery used to heat tube filaments.

Aerial. Wire or other metal used to collect energy from radio waves.

Alternator. A magnetic mechanical device for generating alternating currents.

Ammeter. An instrument for measuring the rate of flow of electricity.

Ampere. A practical unit of current.

Amplifying Factor. Roughly it is the voltage changes occurring in the plate circuit of a tube divided by the magnitude of the voltage changes in the grid circuit which produced them.

Antenna. See Aerial.

Audio Frequency. Frequencies within the range of the human ear.

B

“ B ” Battery. Battery used to supply potential to the plate of a tube.

Battery. A chemical device for supplying a flow of electricity.

Beat Frequency. The sum or difference of two other frequencies.

Bridge. Term used in electricity for an arrangement of resistances, inductances, or capacities, for the comparison of values of any of these three quantities with standards of the same kind.

Buzzer. An iron core wound with a coil of wire and arranged to break its own circuit intermittently.

C

"C" Battery. Battery used to maintain a potential difference between the grid and filament of a tube.

Capacity. The ability of a body to store electricity at a given potential. The ratio of the charge to the potential of a conducting body.

Carrier Frequency. The fundamental frequency of current produced in a broadcasting transmitter.

Choke Coil. A high inductance used to permit the passage of direct currents but to hinder the passage of alternating currents.

Condenser. An arrangement of conductors, usually in the form of plates, for the storage of electricity.

Conductance. The ease with which current passes through a substance. (The reciprocal of resistance.)

Conductor. Any substance through which electricity can be made to flow.

Coupling. Overlapping of electric or magnetic fields from one instrument to another.

Crystal Detector. Arrangement of a metal contact on a crystal, or of a contact between two crystals for the detection of radio signals.

Current. The flow of electricity.

Cycle. (in alternating currents) Complete form of current or e.m.f. during the time of one complete period.

D

Detector. A device for obtaining currents of audio or intermediate frequency from radio signals.

Dielectric. An insulator considered from the point of view of its effect on electric fields.

E

Electro-Magnetic Waves. Energy disturbance which is propagated through space without the need of a known material medium and which is electric and magnetic in its origin.

Electro-Motive-Force. The ability to maintain a flow of current over a circuit in which a potential drop takes place. Abbreviation, e. m. f.

Electron. Smallest known particle of negative electricity.

Electric Field. The force which would be experienced by unit charge of electricity in the vicinity of other charges.

F

Fading. The rising and falling of intensity of radio signals coming from stations other than locals.

Farad. A unit of capacity.

Filament. The part of a three-electrode-tube which is heated and which gives off electrons.

Filter. A device for either facilitating or hindering the flow of certain frequencies of current in comparison to other frequencies present in the same circuit.

Frequency. The number of complete vibrations occurring in one second.

G

Generator. A mechanical magnetic device for supplying electric currents.

Grid. The control element of a three-electrode tube.

Grid Leak. A high resistance used to aid in keeping the grid of a tube in some circuits from departing too far from the potential of the filament.

Ground. The electrical connection of a radio or other electrical device to the earth.

H

Harmonics. Frequencies which are integral multiples of the fundamental.

Henry. A unit of inductance.

I

Impedance. Hindrance to the flow of current, especially in alternating current circuits where capacity and inductance as well as resistance affect the flow.

Inductance. A measure of the magnetic effects of current in a given device, usually a coil of wire.

Insulator. Any substance which conducts electricity to only a negligible degree.

Intermediate Frequency. A frequency above the audible range but below the frequencies ordinarily used in broadcasting.

K

Kenotron. A two element vacuum tube used for rectifying.

L

Lightning Arrester. A device which prevents the flow of lightning discharges in a radio receiver by permitting them to flow directly to the ground.

Loop. A large coil used in place of an aerial as a collector.

M

Megohm. One million ohms of resistance.

Microphone. Device for converting sound vibration into alternating or pulsating electric currents.

Micro-henry. One millionth of a henry.

Modulation. Control of the quantity of current flowing—usually by alternations corresponding to those of music or speech.

Mutual Induction. Contribution to the inductance of one circuit by the current flowing in a neighboring circuit.

N

Neutralization. Term used in radio to denote counteracting the effects of one circuit or part of a circuit by another.

Neutrodyne. A tuned radio frequency receiver employing a type of neutralization due to Hazeltine.

O

Ohm. The unit of resistance.

Oscillator. In radio, a tube and such circuits as may be required for the production of alternating currents from direct current sources of energy.

P

Permeability. The ratio of the magnetic flux in a substance to the magnetizing field.

Phase. The time relation between two vibrations.

Plate. The electrode of a tube which is ordinarily kept at a high potential with respect to the filament.

Potential Difference. Work done in the passage of electricity between two points.

Potentiometer. A resistance connected between two electric lines at different potentials and arranged so that a moveable contact on the resistance enables one to obtain an intermediate potential.

Power. The rate of consumption of electrical energy.

R

Radio Frequency. Strictly speaking, any frequency above the audible. Commonly used to denote frequencies in the broadcast range, i. e., above 500,000.

Radiation. The emission of electro-magnetic energy, ordinarily from an antenna.

Reactance. That part of impedance which is due only to inductance and capacity.

Rectification. Conversion of alternating to direct currents.

Regeneration. The feeding of energy from the output to the input circuit of a tube in amounts which are too small to produce self-sustained oscillations.

Resistance. Hindrance to the flow of electricity which does not displace the phase of the current with respect to the phase of the applied e. m. f.

Resonance. That condition where the natural frequency of a circuit is the same as the frequency of e. m. f. impressed upon it.

Rheostat. A variable resistance.

S

Selectivity. Ability of a radio receiver to separate the signals of stations whose carrier frequencies are close to one another.

Self-induction. A measure of the magnetic effects on a single circuit due to establishment or stoppage of current in the circuit.

Shunt. A conductor placed across the terminals of an instrument.

Shielding. Enclosure made of conducting material to prevent the passage of energy by means of electric or magnetic fields or by means of electro-magnetic radiation.

Static. A term commonly used to refer to undesirable sounds in radio receivers resulting from natural electrical phenomena.

Storage Battery. A chemical device for supplying current in which the chemical action can be reversed by forcing current through in the reverse direction.

T

Telephone Receiver. Device for converting alternating currents into sound vibrations.

Transformer. A term ordinarily applied to an arrangement of two coils whereby electrical energy supplied to the first can be transferred by magnetic means to the second.

Tube. Ordinarily used to denote a vacuum tube containing three or four elements for use in a radio circuit or one containing two elements for use in a rectifying circuit.

V

Vernier. A slow motion device on any variable instrument.

Volt. A practical unit of potential difference and of electro-motive force.

Voltmeter. An instrument for measuring volts.

W

Watt. A unit of power.

Wave-Length. Distance between two corresponding points of energy pulses in space. As applied to radio waves it is the velocity of light (300,000,000 meters per second) divided by the frequency of the carrier current of the transmitter.

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